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ACTIVE EXPERIMENTS IN SPACE IN CONJUNCTION WITH SKYLAB

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## ACTIVE EXPERIMENTS IN SPACE IN CONJUNCTION WITH SKYLAB

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Throughout the year, analyses of past barium shaped charge experiments have continued. A full length paper "The L = 6.6 OOSIK Barium Plasma Injection Experiment and Magnetic Storm of March 7, 1972" by E. M. Wescott et al., has been submitted to the Journal of Geophysical Research for publication. "Observations of Auroral Birkeland Sheet Current From Distortion of Barium Plasma Jet" by E. M. Wescott et al., has been submitted as a Geophysical Research Letter. Copies of these papers are enclosed as Appendices A and B. A third paper on the quiet time L = 6.6 barium plasma injection experiment CHACHALACA is in the final stages of preparation and should be ready for submission in the near future.

The two Black Brant IVA barium shaped charge rockets fired from Poker Flat in conjunction with SKYLAB III were successful and promise to produce very interesting results. Los Alamos Scientific Laboratory and Sandia Laboratories participated in the experiments, providing the high explosive shaped charge and the payload and payload preparation. LASL also flew an NC-135 jet aircraft out of Hawaii to observe the plasma jets.

The first shot, NASA 19.008UA, launched at 1506, November 27, 1973 attained near nominal performance and produced a well-defined plasma jet. Observations by eye and with black and white photography were made for more than 4 minutes from SKYLAB. The photos were out of focus, but use of an astronomical technique of stacking negatives has produced usable data. We have also worked with Jet Propulsion Laboratory personnel in a scan and computer

method of increasing the resolution of the pictures. Sufficient high quality data were obtained from ground stations in Alaska and from the aircraft to triangulate on the streak giving its orientation in space and motion. The shot occurred during an active magnetic situation and high electric fields. Analysis is not yet completed.

The second shot may prove to be the most interesting experiment which we have done to date. NASA 19.009 UA was launched at 1520, December 4, 1973 with nominal performance, also in disturbed magnetic conditions. The jet was observed to travel out into the magnetosphere for 15 minutes with no obvious indication of striation formation except at the very lowest ionospheric altitude. Near event plus 15 minutes striations in the farthest portion of the streak (6 - 12,000 km altitude) were observed to develop rapidly. Within a few seconds there was a brightening of this portion of the plasma of 3X. At event plus 16½ minutes there was a rapid separation and dispersion of the various striations at the head of the jet. After they dispersed we observed that the lower portion (altitude < 6000 km) of the jet remained unaffected, and could still be seen for many minutes, unstriated. Thus we believe we have observed an interaction of the barium plasma jet in a specific space-velocity regime with the ambient magnetospheric particles and waves. A paper on these results was given at the Spring 1974 AGU meeting, which will be enlarged as a complete scientific paper for publication in the future.

APPENDIX A

THE L = 6.6 OOSIK BARIUM PLASMA INJECTION EXPERIMENT  
AND MAGNETIC STORM OF MARCH 7, 1972

by

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\*Work done under the auspices of the U. S. Atomic Energy Commission

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ABSTRACT

The high-altitude detonation of a high explosive shaped charge vaporizes a hollow conical liner of barium metal and produces a fast, field-aligned jet of plasma with approximately one mole of ions having initial velocities distributed from 8 to 20 km/sec. Such a barium plasma injection experiment was performed at 540 km altitude over Alaska ( $L = 6.6$ ) on the evening of March 7, 1972 in an attempt to trace out and observe the dynamics of an auroral field line in the magnetosphere. With image orthicon television systems and image intensified cameras the resulting streak rising into the magnetosphere was observed for 30 minutes and out to 3 Re altitude. A 1.5 m aperture photometer detected the barium streak at  $E + 55$  minutes at nominal look angles where the ions would be near altitude 5 Re and 2 Re from the magnetic

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equator. The injection occurred during a quiescent phase of a magnetic storm initiated by an SSC 10 hours prior to the experiment. Quiet auroral arcs existed over Alaska at locations more than 200 km south of the injection point. The barium flux tube drifted first eastwards and then southward under  $\underline{E} \times \underline{B}$  with velocities of several hundred m/s while also splitting into at least 7 separate flux tubes distributed along 200 km parallel to L. At  $E + 16$  minutes an intense auroral activation and magnetic substorm (the OOSIK substorm) began in the Alaskan sector. Subsequent polewards expansion of the aurora and formation of a classic spiral resulted in the intersection and crossing of the barium flux tubes by an auroral arc. Very rapid, almost turbulent motions of the barium flux observed during the intersection interval resulted from local transient  $\underline{E}$  fields of 200 mV/m directed inwards toward the auroral arc. Observations of the distortion of the barium flux tubes on opposite sides of the aurora as compared with a field model including the super-disturbed external coefficients of Mead and Fairfield (1973) offer compelling evidence for an upward Birkeland current sheet at the poleward edge of the auroral spiral of  $8 \times 10^{-2}$  amp/m. The OOSIK substorm was spatially limited to the dusk sector; it occurred during the decaying phase of a larger substorm observed in the midnight to dawn sector. The substorm and aurora had several unusual features. Examination of the question as to whether the plasma injection may have triggered the substorm unveiled no compelling evidence that it did; however, the unusual features of the substorm leave open that possibility.

## INTRODUCTION

High-explosive shaped-charges with hollow conical liners of barium metal, when carried aloft by sounding rockets, can create field-aligned jets of barium plasma with significant ion densities at velocities from 8 km/sec to 15 km/sec. Ejected upward along the direction of the magnetic field, the plasma jets visibly trace out the field lines. Wescott et al. (1972, 1974) reported successful field line tracing over the entire 7000 km length of  $L = 1.24$  field lines on three occasions. Here we report on a similar experiment conducted on an  $L = 6.6$  field line. This experiment, named OOSIK, is of special interest because complex sequences of events occurring near the time of the experiment raise the question of whether or not the injection experiment modified natural magnetospheric processes. In particular, there was a small, violent and apparently peculiar magnetic substorm some minutes after the injection; this substorm has come to be called the OOSIK Substorm.

FIG. 1 The OOSIK detonation occurred at 0659 UT on March 7, 1972 when the rocket launched northward from Poker Flat, Alaska reached altitude 540 km (areal position  $65.988^{\circ}$  N,  $147.610^{\circ}$  W). See Fig. 1. At the time of the injection there was a magnetic storm underway, and visible auroral arcs were lying several hundred kilometers south of the injection point. Still, the observed magnetic field in the College-Poker Flat area was near its undisturbed value. The plasma jet resulting from solar photoionization of the barium immediately moved easterly and then southeasterly towards the aurora and split up into several distinct plasma tubes which spread out east and west to form, eventually a row of flux tubes 200 km in length along an L-shell. Before the barium flux tubes reached the aurora lying to the

south, a violent substorm onset occurred. The auroras brightened rapidly and evolved into a spiraling configuration which expanded northward to intercept the barium flux tubes. When the aurora and the barium came together, the barium flux tubes underwent complex, rapid motions and then proceeded on southward past the northernmost boundary of the aurora. During this period the orientation of the barium flux tubes was observed to change in a manner that suggests the effect of field-aligned currents terminating in the aurora. By the time the barium flux tubes could no longer be effectively observed with imaging devices, the tips of the flux tubes had reached to near altitude 20,000 km. Later, 55 min after injection, barium was detected near the equatorial plane (altitude  $\sim$  30,000 km) by a sensitive photometer at Rattlesnake Peak, Washington.

#### ROCKET PAYLOAD

The payload, fitting a 9" diameter cylinder on a Tomahawk second stage rocket, essentially consisted of the high-explosive shaped charge with Ba metal liner, an attitude control system, and circuitry for timing and firing. The shaped-charge was 30.4 cm long, 18.0 cm in diameter with approximately 22 kg of 9404 explosive. The barium metal liner was a 5-mm thick hollow cone of  $30^\circ$  total angle weighing 881 gm. An ignitor initiated a plane wave generator at the base of the 9404 cylinder, its detonation was initiated by a G-activated timer switch and battery circuit.

After the payload section was despun and separated from the Tomahawk, the 3-axis attitude control system oriented the axis of the shaped-charge to point upwards parallel to the local magnetic field direction as sensed by fluxgate magnetometers. Telemetry indicated that all systems functioned properly.



The plasma jet produced contained about one mole of  $\text{Ba}^+$  ions, and one minute after detonation it was 9 km in diameter. There was a density maximum near 13 km/sec and lesser concentrations at velocities between 8 and 20 km/sec.

#### OBSERVING INSTRUMENTATION

##### Ground-based Optical Instrumentation - Various participants

in the experiment operated a variety of optical instruments at several widely-spaced locations. The instruments included photographic cameras, image orthicon televisions (TV), image intensifier cameras and scanning or pointable photometers. We note only those particular instruments yielding data used here. Figure 1 shows the positions of many of the observing stations listed below.

At Barter Island, Alaska ( $70.13^\circ$  N,  $143.64^\circ$  W), 500 km north of the injection point, there was an image orthicon TV which operated with excellent viewing conditions through the period of interest. Barter Island is located relative to the injection point such that a line of sight becomes tangent to the barium streak near 5000-km altitude. This geometric relationship proved especially useful. The Barter Island TV was operated in an unfiltered, real-time mode to yield 60 images/sec during the first 10 minutes after barium injection. Thereafter it viewed through a  $4554 \text{ \AA}$  ( $\text{Ba}^+$  line) narrow band filter with much greater sensitivity in integration mode to produce one image each few seconds. The last observations of the barium were at 30 min after injection (E + 30 min).

At Ester Dome, Alaska ( $64.88^\circ$  N,  $148.05^\circ$  W), 100 km south of the injection point and in the College vicinity, there were auroral all-sky cameras and a three-camera color TV system. The full TV system

operated through filters for two minutes when the red filter was removed from one camera to operate in white light while all were operated in real-time mode up to E + 10 min. Thereafter one of the three cameras operated with a 4554 Å filter in integration mode, as at Barter Island, and the others continued in real-time mode. Moisture in the local atmosphere caused faint haze and increasing opaqueness in view directions away from the zenith. Consequently, observing conditions were far from perfect, and useful tracking information resulted only up to E + 10 min. However auroral conditions could be well determined for the entire period of interest.

An image intensifier camera at Johnston Island (16.8° N, 169.6° W), 5800 km south of the injection point, yielded useful images every few seconds until E + 13 min, by which time the barium streak was observed up to 35° elevation above the north horizon.

The Batelle Northwest Laboratories group (Hoch et al., 1972) at Rattlesnake Peak, Washington (46.29° N, 119.41° W), 2800 km southeast of the injection point, operated a sensitive, large-aperture (150 cm) pointable photometer which was able to detect barium ions near the equatorial plane region up to E + 55 min. This group also operated an almucantar scanning photometer stepping in elevation angle to observe auroral emissions over the whole sky once each 5 min. Recordings of 6300 Å and 5577 Å were made on every scan and of 5577 Å emissions on every third scan (15 minutes apart).

Photographic and visual observations were made at a number of locations in Alaska; a visual sighting of the barium plasma was reported at Pine Mountain, Oregon.

Other Instrumentation - Magnetometers were in routine operation

at various Alaskan stations, and G. B. Carpenter (1972) operated a sensitive cryogenic magnetometer near the base of the injection field line at Venetie, Alaska ( $66.64^{\circ}$  N,  $145.98^{\circ}$  W) and also a VLF recorder. A VLF recorder also was operated nearby at Fort Yukon, Alaska ( $66.63^{\circ}$  N,  $145.22^{\circ}$  W).

Personnel of SRI and the Geophysical Institute operated the Chatanika incoherent scatter radar, located adjacent to Poker Flat, in modes to determine ion drift and possible enhancements of electron density near the base of the field line on which the injection occurred. A 50-MHz auroral radar as described by (Balsley et al., 1973) was operated by NOAA at Anchorage, Alaska ( $60.2^{\circ}$  N,  $149.9^{\circ}$  W), and a VHF/UHF/L-band radar was operated by SRI at Homer, Alaska ( $59.7^{\circ}$  N,  $151.5^{\circ}$  E) (Carpenter, 1972).

#### DATA REDUCTION METHODS

A major task in data reduction is the use of triangulation methods to determine the location and configuration of a visible barium plasma tube. The method employed (Wescott et al., 1974) uses star backgrounds to enable accurate angular coordinates to be assigned to points on images on photographs or photographic reproductions of TV data. A computer code is used to calculate a set of up to 20 discrete points in space lying along the segment of a plasma tube observed from two locations, such as Ester Dome and Barter Island. The diffuse edges of a barium plasma tube and error in locating image points relative to the star background introduce an uncertainty of approximately 1 min of arc in the look angles. As a consequence, there is uncertainty of order 1 km in locating the lower (ionospheric) end of a plasma tube. The short baseline of the Ester Dome-

Barter Island station pair, 625 km, limits the accuracy of the triangulation solutions at the upper end of the plasma tube - at altitude 7000 km the estimated uncertainty in altitude is  $\pm 30$  km. Triangulations between image intensifier photographs taken at Johnston Island and images from either Ester Dome or Barter Island yielded results in agreement with triangulations involving only the latter station pair.

Particularly in dealing with motions of entire barium plasma tubes, it is convenient to normalize the observations by transforming them to a common datum altitude, usually 100 km. This is accomplished through application of a field model; for this purpose the POGO 10/68 field model of Cain and Langel (1971) is used.

FIG. 2 The favorable location of Barter Island relative to the visible barium plasma tubes provides another useful technique for locating the geomagnetic field occupied by a plasma tube. As is seen in Fig. 2, a dipole-like field line with base south of Barter Island has an apparent turnover point. Measurement of the elevation angle and azimuth of this point uniquely defines the field line location so that its position in the 100-km datum plane can be found. The same principle can be applied to compare the configuration of a plasma tube observed from Barter Island with the configuration of a model field line seen from the same location. To accomplish this purpose we traced model field lines up from the 100-km datum plane and plotted their positions against a star background using astronomical look angles calculated for Barter Island. We used the POGO 10/68 field model combined with the recently-available time, season and magnetic activity dependent external source perturbation coefficients of Mead and Fairfield (1973). Other field models against which we have compared

the triangulated flux tube configurations include POGO 8/69 (Cain and Sweeney, 1970), IGRF (Cain and Cain, 1971), USGS (Hurwitz and Fabriano, 1969), GSFC 9/65 (Hendricks and Cain, 1966), GSFC 12/66 (Cain et al., 1967) and OGO 2, 4, 6 (R. A. Langel, private communication, 1972)

#### GEOPHYSICAL ENVIRONMENT AT THE TIME OF THE EXPERIMENT

Some 10 hours prior to the OOSIK barium injection, at 2108 on March 6, 1972, there occurred a world-wide SSC. During the 2½-hour initial storm phase following the SSC, the Honolulu  $\Delta H$  rose to +50 $\gamma$  (see Fig. 3). The magnetic storm main phase began near 2330. Its maximum Dst excursion occurred in the hour just prior to the OOSIK experiment (see Table I); at Honolulu the largest negative excursion in  $\Delta H$  was achieved near 0650, just 10 min before the OOSIK experiment. Thus the geomagnetic field was moderately inflated by a well-developed ring current at the time of the experiment.

Near the time of the experiment Hoch et al. (1972) observed at Rattlesnake Peak a sub-auroral red (SAR) arc near  $L = 2.8$ . This observation leads to the estimate (by Hoch et al., 1972) that the plasmopause was near  $L = 3.1$ , following after Taylor et al. (1968). Based upon the SAR arc position and comparisons by Hoch et al. (1972) and Frank (1967), it is probable that the peak density of the ring current was at  $L \leq 4.2$ .

The reproductions of H-component tracings from high-latitude magnetograms in Fig. 4 show the occurrence of substantial substorm activity in the interval following the SSC up to about 02 hours on March 7, 1972. A minor substorm around 04 hours was accompanied by giant pulsations, particularly evident at Meanook, Abisko and Dixon Island. A very large substorm began near 0536. At Narssarssauq, in the early morning sector, it produced a 1000  $\gamma$  negative bay in H. By the time of the OOSIK experi-

ment, this substorm had reached its maximum and was starting to decay. However, at College, the magnetic field was near its undisturbed level; see Fig. 4.

As darkness fell over Alaska on the evening of March 7, 1972 auroras were observed at  $L = 5$  to 6 from 0515 onward. Generally arc-like, these became brighter up to 0600. After 0600, up to the time of the OOSIK experiment at 0659, the auroras over Alaska became quiet and were observed only to the south of College near  $L = 5$ . Though no aurora bright enough to be recorded on all-sky cameras occurred poleward of  $L = 5$ , the radars at Anchorage (Warner Ecklund, private communication, 1972) and Homer (Carpenter, 1972) detected field-aligned irregularities in this region poleward of  $L = 5$ . Mappings of the auroras at 0546 to 0532 are shown in Fig. 5. These are inclined relative to lines of constant  $L$ , implying that auroras to the east of Alaska were probably at lower  $L$  values. Auroras recorded by an all-sky camera at Fort Smith, Canada ( $60^{\circ}$  N,  $112^{\circ}$  W,  $L = 7.1$ ) were only at the southern horizon equatorward of  $L = 3.7$  prior to the OOSIK injection (Gordon Rostocker, private communication, 1972). Also the auroral photometer operated at Rattlesnake Peak, Washington ( $L = 2.8$ ) by Hoch et al. (1972) detected emissions at north elevation angles  $10^{\circ}$  to  $20^{\circ}$ , implying auroral forms at  $L = 3$  to 3.5, in agreement with the Fort Smith observations.

Pertinent also to the geophysical setting at the time of the OOSIK experiment is the interplanetary medium. Interplanetary field data from HEOS-2 (N. E. Hedgecock, private communication, 1973) shows that the interplanetary shock responsible for the SSC at 2108 on March 6 was followed for several hours by rapid changes in magnitude and direction. We

note from Fig. 4, that this is the period of several short substorm events. By 0200 on March 7, following a two-hour data dropout, the interplanetary field was observed to be steady, northerly and towards the sun. Between 0400 and 0500, the field changed from north to south and back northerly. There were multiple bow shock crossings by HEOS-2 just prior to and during the OOSIK experiment, but there were no obvious changes in field direction on any of the crossings in the hour 0600 to 0700, and the interplanetary field appears to have been smoothly changing throughout to more northerly. L. Svalgaard (private communication, 1973) estimated from the Thule magnetograms that the interplanetary field was generally towards the sun before March 7; on that day it was mixed and then for 8 days thereafter the field was away from the sun. Thus within some hours of the OOSIK experiment the earth probably crossed a sector boundary.

#### RESULTS

Since it was our first attempt to perform a shaped-charge barium experiment at the auroral zone, we intended that the OOSIK experiment be during undisturbed conditions. However, various circumstances led to the decision to launch the rocket during a magnetic storm at a time of relative quiescence in the immediate vicinity, even though aurora lay well equatorward of the injection point. Owing to the complexity of the behavior of both the barium plasma and the aurora following the injection, we attempt here to simplify the description by discussing individually the various phenomena observed rather than to follow a strictly chronological presentation.

Flux Tube Splitting - As is seen in Fig. 2, the plasma jet produced by the detonation soon split into multiple flux tubes. By  $E + 3$  min, at

least two separated tubes are evident; by E + 13 min, when the Barter Island TV began operating in the sensitive integration mode, three bright flux tubes are evident, as are at least four more weaker flux tubes. The separated flux tubes spread out approximately parallel to surfaces of constant L (also, approximately parallel to the orientation of the auroral arcs) until the flux tubes were distributed over a distance of approximately 200 km. Owing to the threshold of detectability, resolution and background level, it is not possible to determine if there is a weak, diffuse connection between the apparently separated barium flux tubes. The distribution of the separated flux tubes, at times from E + 13 min to E + 21 min, is seen in Fig. 6 which presents the time track at altitude 100 km of the bases of the observable flux tubes which evolved from the original plasma jet. With a few exceptions, the positions shown in Fig. 6 were plotted at 1-min intervals using triangulated data points traced downwards to 100-km altitude through the POGO 10/68 field model or by comparing locations of observed and theoretical field lines as seen from Barter Island. The latter method, described in the section on data reduction methods, utilized the POGO 10/68 combined with the Mead-Fairfield (1973) external source coefficients.

Flux Tube Convection - Figure 6 shows that the original plasma jet (and its visible offspring) immediately moved southeasterly nearly parallel to L until E + 6 min. Then it moved more southerly until E + 30 when it could no longer be observed. Complex motions undergone when the barium flux tubes intersected the aurora at E + 19 min are described below. Ignoring these complexities, we see that the general (convection)



motion was first southeasterly, then southerly at speeds near 400 m/sec, indicating a substantial westerly convection electric field.

The OOSIK Substorm - For 16 min after the OOSIK injection, the magnetic field measured at College showed little change, and the auroral arcs to the south changed little. In the meantime, the original barium jet was drifting southerly toward the aurora, the original flux tube was splitting up into flux tubes aligned parallel to the aurora, and the flux tube tips were moving upward to reach an altitude of approximately 13,000 km by E + 16 min.

At 0715:20 (E + 16<sup>m</sup> 20<sup>s</sup>) the College magnetogram H trace took a sudden negative plunge to reach  $\Delta H \approx -430\gamma$  within the following few minutes; see Fig. 7. Simultaneously, the auroras south of College, brightened, began to show minor convolutions and began to expand northwards. The auroral behavior is shown by the all-sky photographs reproduced in Fig. 8. There, the all-sky frames are printed as if the observer were above the earth looking down on the aurora (magnetic north at top, magnetic east at right). Print exposures after E + 15<sup>m</sup> 20<sup>s</sup> are half those of the earlier photographs to better show the details of the brighter auroras existing after E + 15<sup>m</sup> 20<sup>s</sup>.

Figure 8 and the auroral mappings presented in Fig. 9 show that the array of barium plasma flux tubes was 100 km to 200 km northward of the aurora when the "OOSIK Substorm" began. In Fig. 9, the positional accuracy of both the barium and the auroral mappings near the intersections of the two is approximately 10 km. Proximate to the barium flux tubes, an auroral spiral evolved out of the pre-existing auroral arcs. Its northern limb came into contact with the barium flux tubes at E + 19 min. The barium flux tubes underwent turbulent motions for a brief time and continued

their general southward drift through the aurora. Visual observers in Central Alaska were impressed by the brightness and rapid motions of the aurora, perhaps in part because it is not usual to observe such a brilliant display this early in the evening.

Turbulent Barium Plasma Motions - Superposed on the generally southward drift of the barium plasma tubes near time  $E + 19$  min was a complex turbulent motion observable from Barter Island where a TV field was obtained every 4 seconds. When each TV field is filmed as one movie frame, then shown at 16 frames/sec the motion is very much speeded up (64X) and the eye can easily see the relative turbulent-like motions of the various visible streaks. It is apparent that the most western rays become accelerated a few seconds prior to the easternmost rays. This agrees with the auroral data from the all-sky camera frames which show eastward propagating auroral irregularities on the northern limb of the westward propagating auroral spiral.

It was of interest to determine where the barium plasma tubes were with respect to the auroral shells when the rapid motions were seen. Based upon an assumed height of the auroral lower borders of 100 km, the auroral positions for each available all-sky camera from from  $E + 18^m40^s$  to

*FIG. 10*  $E + 19^m54^s$  were plotted in Fig. 10. Likewise, the positions of the foot of the barium flux tubes (at 100 km) were determined. The positional accuracy of the barium is probably between 5-10 km, and that of the auroras the same order. The results in Fig. 10 show that the barium was near the polewards boundary of the aurora.

Velocity vectors, determined from the incremental positional data are shown for the various streaks which could be identified. Two of the

streaks, as indicated on Fig. 10 by the largest dots, were brighter and more clearly defined on the TV frames and therefore more accurately located on the maps. Prior to  $E + 19^m 14^s$  the barium is all polewards of the aurora, but with very rapid eastward motion. At  $E + 19^m 20^s$  the most poleward aurora appeared north of the main barium streaks. At this time the main streaks accelerated southward and then westward. The harmonic dial diagram in

FIG. 11 Fig. 11 shows the end points of velocity vectors of a barium flux tube located at the west end of the flux tube array during the  $1\frac{1}{2}$ -min interval starting at  $E + 18^m 24^s$ . The motion of the flux tube is seen there to change from 3900 m/sec eastward to 3400 m/sec westward in only a few seconds, starting at  $E + 19^m 06^s$ . To our knowledge these are the fastest ion motions yet observed using the plasma release technique.

Field Line Distortion - The several field models mentioned in the section on data reduction were compared with the observed barium flux tube configurations determined by triangulation. In all cases representing configurations prior to  $E + 19$  min, the observed flux tubes were found to be distorted relative to the field models; the distortion was away from the solar direction towards the magnetotail, even within 1 Re altitude.

The best fit found was obtained by combining the coefficients of the most disturbed ( $K \geq 3$ ) model of Mead and Fairfield (1973) with the coefficients of the POGO 10/68 model (Cain and Langel, 1971). Still, the disagreement

FIG. 12 is significant, as is seen in Fig. 12, which is for  $E + 9$  min. For times later than  $E + 9$  min, when the plasma tubes have penetrated farther out into the magnetosphere, the distortion away from the Mead-Fairfield dis-

FIG. 13 turbed model is even greater. Figure 13 shows portions of the seven plasma

tubes as observed from Barter Island at E + 16 min. Superposed on the brightest (the original) plasma tube is the Mead-Fairfield ( $K_p \geq 3$ ) model field line, with distance along the field line in 1000-km increments indicated. The model and observed field lines coalesce up to 5000 km, but diverge monotonically at greater distances. The palpable end of the plasma tube is between 10,000 km and 11,000 km, which is the distance ions injected with initial velocity 14 km/sec would reach by this time. Considering the view direction of the photograph of Fig. 13, the observed departure from the field model can be interpreted as a displacement of the end of the flux tube eastward back toward the magnetotail or as a displacement toward lower altitude in the plane of a plot of altitude versus latitude.

Between the time represented by Fig. 13, E + 16 min, and that represented *FIG. 14* by a similar diagram shown in Fig. 14, E + 19<sup>m</sup> 33<sup>s</sup>, the barium plasma tube had intersected the auroral spiral and passed equatorward of its northernmost edge. Although the plasma tube is not distinct in the reproduction, Fig. 14, now is distorted westward of the theoretical field line, i.e., in the opposite sense to the distortion shown at the earlier time in Fig. 12. There is no doubt that the configuration of the barium plasma tube radically changed as the tube crossed the aurora.

After E  $\approx$  21 min, the barium flux tubes could not be usefully observed with imaging devices. However, the sensitive photometer operated by Hoch et al. (1972) at Rattlesnake Peak continued to detect barium ions up to E + 55 min. At this time, repeated photometer scans at elevation angle 35°, azimuth 247° last detected barium emissions. The L-value of the field lines occupied by the barium is unknown at this late time. However, barium ions with an initial velocity of 14 km/sec along an L = 6 field line would

be detected at the appropriate angles at Rattlesnake Peak at E + 55 min. By then the upper tip of the barium plasma would be at altitude 30,000 km and within 10,000 km of the equatorial plane.

#### DISCUSSION AND CONCLUSIONS

The observed divergence between the plasma tube shown in Fig. 13 and the Mead-Fairfield  $K_p \geq 3$  disturbed model could be the result of inadequacy of the model to incorporate enough disturbance distortion for the particular time of the OOSIK experiment. However, since the model was derived using only satellite data acquired during highly disturbed conditions, it seems more likely that an additional perturbing influence was present. Furthermore, the divergence seen in Fig. 13 is absent or in the opposite sense in Fig. 14, which depicts the flux tube three minutes later after it has crossed one of the auroral arcs. The change in orientation of the barium plasma tube suggests the existence of an upward field-aligned current along the field lines terminating in the aurora. In order to investigate this possibility we have calculated the angular divergence between the observed flux tube (Fig. 13) and the model field as a function of altitude, the local  $\Delta B$  perpendicular to the field required to produce the angular divergence, and the current required if an infinite upward sheet current was located in the aurora to the south. The results are shown in Table II. Owing to the increasing separation with altitude of the magnetic field lines carrying the current, the current density should decrease with altitude. When this factor is taken into account, the data points fit within 5% to a current sheet with typical current  $8 \times 10^{-2}$  amp/m. The plasma tube shown in Fig. 14 is too indistinct to allow a similar computation, but the data shown there are compatible with the existence of such a current

sheet above the aurora.

Cloutier et al. (1970), Vondrak et al. (1971), Cloutier et al. (1973) have reported results from rocket-borne magnetometer and particle detectors which can be explained by infinite current sheets -- one downward near the equatorward boundary of an auroral band and one upward near the poleward edge. The current they calculate is of order  $10^{-1}$  amp/m, in good agreement with our calculation based on the observed field line configuration. Similarly, Armstrong and Zmuda (1970) have found evidence in satellite measurements near 1100 km altitude for field-aligned currents of such magnitude.

In the instance we have observed it is particularly interesting that the aurora intersected by the equatorward-drifting barium flux tube was part of a classic spiral configuration. Hallinan et al. (1972) and Webster and Hallinan (1973) have proposed that the auroral spiral configuration is the result of instability in a field-aligned sheet current when the current reaches a threshold value compatible with our calculated current. Thus we conclude that the observed distortions to the barium flux tubes are, in part, direct evidence of a field-aligned current of  $\sim 8 \times 10^{-2}$  amp/m in the auroral sheet. When the distortion caused by such a current is subtracted away, a reasonable fit to the Mead-Fairfield highly-disturbed ( $K_p \geq 3$ ) field model is obtained.

The motion of the primary barium plasma tube, generally eastward parallel to L during the first 6 min and then more southerly towards and across the aurora until it can no longer be followed, after E + 21 min, can be interpreted as  $\vec{E} \times \vec{B}$  drift due to a convection electric field. Using

that interpretation, the electric field components (at 100 km altitude) derived are presented in Fig. 15. There the electric field is seen to have a relatively steady southward component ranging up to 30 mV/m up until the time when the barium plasma tubes intersected the aurora at about E + 19 min, at which time the component perpendicular to L reverses to become predominately southward. Throughout the interval the electric field component parallel to L remains almost entirely westward and is more variable with time than the perpendicular component. The westward component of  $\vec{E}$  drives the barium plasma southward across the northern boundary of the aurora. Ion drift measurements made by the Chatanika incoherent radar during the interval are in substantial agreement with

FIG. 15 the data shown in Fig. 15.

It is clear that the polewards motion of the aurora during the activation starting at E + 16 min was not a direct consequence of the magnetospheric electric field, since the barium flux tubes moved in the opposite directions. Similar conclusions based upon relative motions between thermite-released barium clouds and auroras were previously reached by Wescott et al. (1970).

The complex turbulent motion of the barium plasma tubes in the short interval near E + 19 min (see Figs. 10 and 11) appears to be caused by a source other than the general magnetospheric electric field. Since these turbulent motions occurred just when the barium flux tubes intercepted the northern limb of the auroral spiral developing at the time, and since the flux tube motions were similar to the motions of auroral irregularities within the spiral, we interpret the turbulent motions as being caused by a transient, spatially structured electric field associated with the

spiral. The observed motion of the barium flux tubes when near the aurora, translated into electric fields, indicates that the  $\vec{E}$ -field vectors point inwards to the auroral form in this case. Such a field could be explained by a negative space charge across the auroral form. Applying Gauss' law, and assuming  $\Delta\vec{E} = 300$  mV/m across the surface we find a space charge of  $6.265 \times 10^{-12}$  coulomb/m<sup>2</sup>. This calculated surface charge alone is insufficient to explain the  $8 \times 10^{-2}$  amp/m Birkeland current calculated earlier; also Rassbach (1973) has concluded, on the basis of calculation, that upward Birkeland current must be principally carried by upward moving positive ions. According to T. J. Hallinan (private communication, 1974) the high electric field observed here is expected in association with the spiral.

The turbulent motion of several of the observed barium flux tubes *FIG. 16* is shown in Fig. 16 in the form of electric field components directed magnetically southward and westward. The very high transient electric field magnitude shown, up to 200 mV/m, is larger than any observed by rocket or satellite sensors or by incoherent scatter radar. We suspect that such high field values may occur frequently but that the transient and localized nature of such fields is the explanation for their not being detected by those other methods. In fact, the observation of a high transient electric field near to an aurora, at first sight, appears contradictory to the previous reports by Aggson (1969) and Wescott et al. (1969) that  $\vec{E}$  fields are generally low to non-existent in the L shell containing a bright aurora. However, the observations presented here do not suggest that the electric field is large precisely at the location of an auroral form, only that it is very large nearby; furthermore, Wescott et al. (1969)



also observed at least one instance of substantial E-field ( $> 100$  mV/m) within 10 km of the polewards boundary of an auroral form.

To examine the magnetospheric convection, the positions of the principle barium flux tube indicated in Fig. 6 have been transferred through the Mead-Fairfield disturbed field model to the magnetic equatorial plane *Fig. 17* (minimum B surface) and the results plotted on Fig. 17 together with the similarly transformed general locations of auroras observed from Alaska, Canada and Washington State. Arrows indicate the directions of the convection electric field at the equator's plane derived from the barium flux tube motions; the electric field magnitude in the reference frame of the non-rotating magnetosphere ranges from 6.5 to 17 mV/m at the minimum B surface. It is interesting that the region sampled extends from 35,000 km to 50,000 km geocentric distance. The observed convection in this portion of the dusk sector of the magnetosphere, being nearly cross-tail, is at variance with suggested convection patterns of Axford (1969), Wolf (1970) and Davis (1971) unless those patterns are shifted well inward and rotated toward the dusk meridian.

Horizontal gradients in the electric field may well have contributed to the wide separation observed between the individual barium flux tubes which evolved from the original plasma injection and may perhaps also have contributed to the rapid splitting up of the parent flux tube. We note that plasma injection experiments at  $L = 1.24$  (Wescott et al., 1974) with identical payloads and similar altitude of injection produced well-confined plasma jets over 7000 km long. Flux tube splitting sufficient to be observed with TV or image intensifier cameras did not develop until late time when the barium had reached an altitude in the conjugate iono-

sphere where interaction with neutral wind became significant.

There are several possible explanations for flux tube splitting in barium plasmas. Most ion clouds produced by thermite barium releases at ionospheric altitude have been observed to split up into sheets which then evolved filamentary structures (Rosenberg, 1971; Davis et al., 1974). Called striation development, the process has been ascribed by most authors to the gradient  $\underline{E} \times \underline{B}$  instability (Linson and Workman, 1970; Völk and Haerendel, 1971) which is related to the differential motion of the barium ions with respect to the neutral wind. Striations also have been observed to develop in barium thermite releases at very high altitudes in the magnetosphere where there is no neutral atmosphere (Völk and Haerendel, 1970; Mende, 1973). In these cases, the early striations are thought to arise from a Rayleigh-Taylor instability during the deceleration phase of the expansion of the ion cloud (Haerendel and Lüst, 1970; Pilipp, 1971).

The OOSIK experiment differs from the thermite releases in the ionosphere and those farther out in the magnetosphere since at the altitude of the release, 540 km, there is negligible interaction with neutrals, and the magnetic field is strong. The flux tube splitting observed during the OOSIK experiment is discussed more fully in another paper by Bottoms et al., (1974) wherein it is suggested that the OOSIK splitting is caused by small-scale irregularities in the high ionosphere that are impressed upon the original flux tube during formation.

The final topic to be discussed is the OOSIK Substorm, its nature and whether it was caused by the barium plasma injection performed 16 min before the onset. The magnetic signature of this event at College, an

abrupt 400 $\gamma$  negative excursion in the H component starting at E + 16 min and maximizing 3.5 min later, is rarely observed at this location so early in the local night. Excursions of similar magnitude are not uncommon, but usually those observed in early evening at College have more gradual onsets similar to the bay in the Meanook record which occurred essentially simultaneously with the event at College; see Fig. 4. A search of all College magnetograms obtained in 1972 and 1973 yields only a few examples of early-evening bays in H with onsets similar to the event at E + 16 min. Thus it appears that the bay at E + 16 min probably is unusual rather than unique in character; its rapid onset probably means that the activity causing the bay originated very near to College. As shown by Fig. 4 the negative bay event observed at College and Meanook was not large enough to affect the AE index for the interval because more intense longitudinal currents were flowing elsewhere, particularly in the morning sector.

FIG. 18 The isolated nature of this event is emphasized by Fig. 18 which shows horizontal disturbance vectors plotted for the time of the peak of the "OOSIK Substorm", 0720. At this time, horizontal disturbance to the west in Siberia and to the east in Canada is essentially absent.

Concurrent with the negative bay development at E + 16 min the auroral arcs lying south of College began to brighten and expand north and south. It is not obvious whether new arcs developed at this time or if pre-existing arcs spread farther apart in latitude. The northernmost arc is seen in Figs. 8 and 9 to be developing convoluted structure and to be moving northward from E + 17 min onward. By E + 20<sup>m</sup> 40<sup>s</sup>, the convoluted structure has developed into, just east of College, the classic spiral configuration described by Hallinan et al. (1972) and Webster and

Hallinan (1973).

As regards the question of whether the OOSIK barium injection experiment caused the "OOSIK Substorm", several observations seem significant. One is that the southward moving barium plasma was still at least 100 km northward of the aurora at E + 16 min when the negative bay and the auroral activation began. Then the tip end of the plasma tube was near altitude 2 Re and had a barium ion density of about 500/cc. There is no evidence of any enhanced auroral precipitation in the immediate vicinity of the ionospheric intersection of the barium flux tubes. Neither the VLF receiver operated by Carpenter (1972) near the base of the barium injection field line at Venetie nor the receiver at Fort Yukon recorded any unusual emissions attributable to interactions between the barium and ambient plasmas at the early time when the barium flux tubes were close to the zenith. When the OOSIK Substorm began the plasma tubes were approximately 100 km south of those stations. Nor were unusual enhancements detected in this region by the Chatanika incoherent scatter radar or the radars at Anchorage (Balsley et al., 1973) and Homer (Carpenter, 1972). Thus it seems that if the barium injection did cause the magnetic and auroral activity, it is necessary to invoke a mechanism which allows triggering at a location somewhat removed from the position of the barium plasma.

Yet another observation bears on this general question. The auroral photometer operated by Hoch et al. (1972) at Rattlesnake Peak, Washington detected a characteristic broad peak of auroral emission to the north-northeast and also detected an unusual sharp peak in the north-northwest near the azimuth of the OOSIK barium plasma. This sharp enhancement

was obvious by E + 7 min and grew to prominence as the "OOSIK Substorm" developed. A search of several years records failed to show any similar auroral signals. Hoch et al. (1972) suggested that trapped energetic electrons suffered strong pitch angle diffusion in the vicinity of the plasma jet, continued drifting eastward and then began to precipitate as the south drift under  $\underline{E} \times \underline{B}$  lowered their mirror attitudes. However, examination of the 6300 Å scans at 10° elevation taken 3 min before and 2 min after the OOSIK injection experiment also show a slight peak near the OOSIK azimuth. Consequently, there is some doubt that the sharp growing enhancement along this azimuth can be associated with an effect due to the barium injection. A possible interpretation of the peculiar auroral emission observed at Rattlesnake Peak is that an auroral arc lying near  $L = 3.5$  to 4 and terminated on its eastern end moved eastward into the view of the photometer. Considering the auroral orientation shown in Fig. 5, it is likely that such an aurora would have been connected with the aurora seen south of College at the time of the experiment.

There is no compelling evidence to permit us to conclude that the OOSIK barium injection caused the "OOSIK Substorm". Yet the many peculiar characteristics of the auroral and magnetic activation justify it being considered unusual, and so we must leave open the possibility that its occurrence was more than coincidental.

Actually, to refer to the observed magnetic and auroral activation as the "OOSIK Substorm" may be somewhat misleading, especially if we reserve the term substorm for global events. The data show that it is an "isolated substorm" limited to the dusk region of Alaska and Western Canada. Probably it is the expression of an increase in field-aligned current and consequent

spiral formation. Increasing knowledge about auroral morphology suggests that several such events might occur within a single global substorm and that this particular event is unusual only in that it occurred so early in the evening.

#### SUMMARY

The OOSIK shaped-charge barium injection performed at altitude 540 km on an  $L = 6.6$  field line over Alaska at 0659 on March 7, 1972, produced a high speed plasma jet traveling upward along the magnetic field. As the original jet elongated and drifted southward under the influence of a westerly electric field, it split up into six or more individual flux tubes without apparent interconnection. These tubes evolved by  $E + 16$  min into a linear array extending 200 km in length along the direction of the ionospheric intersection of an  $L$  shell and also parallel to auroral arcs lying well to the south of the injection point.

At  $E + 16$  min, an intense auroral activation and sharp magnetic bay which was confined to the dusk sector of Alaska and western Canada began. By  $E + 20$  min the aurora had developed into a classic spiral formation which had intersected the barium flux tubes near  $E + 19$  min, 20 sec. The following results and conclusions were derived from analysis of the streak and auroral positions and motions:

1. The flux tube splitting and separation along  $L$  shell direction is thought to be due to pre-existing irregularities and shears in the  $E$  field.
2. The general field line convection was cross tail (inward) during the twenty minutes of useful observation, resulting in an  $E$  field of approximately 30 mV/m at ionospheric altitudes.

3. The northward motion of the auroral forms (spiral development) was not caused by the magnetospheric convection as the barium was moving in the opposite direction and they intersected.
4. Near the time of the intersection E fields of approximately 200 mV/m first southward and then northward were deduced from the almost turbulent motions of the observable flux tubes.
5. The very large, probably transient and spatially limited E fields deduced from the flux tube motion near the auroral intersection suggest a negative charge accumulation of  $6 \times 10^{-12}$  coulomb/m<sup>2</sup> in the auroral arc forming the north limb of the spiral.
6. Distortion of the plasma flux tubes eastward prior to the auroral intersection and westward afterwards as compared with theoretical field lines using the Mead-Fairfield super disturbed ( $K_p \geq 3$ ) external coefficients, are consistent with an upward current sheet near the north side of the aurora of  $8 \times 10^{-2}$  amps/m.
7. The upward current deduced is consistent with other rocket and satellite measurements and is near the critical value suggested by Hallinan et al. (1972) to initiate spiral formation in auroras.
8. Barium ions were last detected at E + 55 min with a sensitive photometer at an azimuth and elevation where ions on a near dipole-like field line would be at 30,000 km altitude and 10,000 km from the magnetic equator.
9. The OOSIK Substorm was restricted to the dusk sector and occurred during the decaying phase of a larger substorm observed in the midnight to dawn sector.
10. There are several unusual features of the substorm, but there is no

compelling evidence to prove that the plasma injection triggered the substorm.

11. The technique of injecting barium plasma with escape velocity upward on auroral zone field lines is a powerful tool for investigating the configuration and dynamics of the magnetosphere.

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TABLE 1

Dst and Kp Prior to and During the OOSIK Experiment;

Dst values are after Sugiura and Poros (1972); Kp after Lincoln (1972)

MAR 6, 1972

MAR 7, 1972

UT	20	21	22	23	0	1	2	3	4	5	6	7	8	9	10
Dst ( $\gamma$ )	-14	28	16	-13	-37	-49	-48	-36	-35	-68	-76	-65	-50	-23	
Kp	2		7+				6+		6			5		5+	

TABLE 2

## Magnetic Field Distortion and Sheet Current Parameters

Altitude Range (km)	Divergence (Degrees)	$\Delta B$ ( $\gamma$ )	$\underline{J}$ (amps/m)
7,000-8,000	0.579	49.7	$7.9 \times 10^{-2}$
8,000-9,000	0.678	47.5	$7.6 \times 10^{-2}$
9,000-10,000	0.780	45.1	$7.2 \times 10^{-2}$

## FIGURE CAPTIONS

- Fig. 1 Composite showing the geometry of the OOSIK field line and the location of some of the observation sites used during the experiment. Heavy part of the field line shows portion traced out by imaging observations of the barium jet.
- Fig. 2 Series of TV frames of the barium jet as observed from Barter Island,  $\sim 360$  km north of the release point. The frame in the upper left corner shows the ion jet 17 sec after the release. The front of the well-defined plasma jet is traveling upward along the magnetic field line with a velocity near 14 km/sec. Between 1 and 3 minutes after the injection, the streak is seen to have split into at least two. The point of the jet reaches the tangent point to the field line between  $E + 5$  and  $E + 8$ ; the tangent point is near 5000 km from the burst point (compare with Fig. 1). After  $E + 8$  min the TV was operated with greatly increased sensitivity and the numerous arches into which the jet has split are clearly seen. The barium arches underwent rapid motions near  $E + 19$  min and were shortly thereafter lost from view.
- Fig. 3 The H-component of the Honolulu magnetogram for the magnetic storm during which the barium shaped charge experiment OOSIK took place.
- Fig. 4 H-component magnetogram traces from a number of auroral zone stations. At the bottom is the AE index derived from the data shown and the College H trace near 07 hours (dashed line).
- Fig. 5 Map of the auroral 100 km lower borders observed at 0547 UT, about an hour prior to the OOSIK experiment. Coordinates are geographic



north latitude, west longitude. The symbols F and E mark the locations of Fort Yukon and Ester Dome, respectively.

Fig. 6 Map showing drift of the field lines marked by the barium. The positions are the 100 km altitude points of the marked field lines; the numerals indicate time in minutes after the injection. The data points up to 10 min are based on triangulated data whereas the later data points have been determined by comparing the TV observations from Barter Island with field model data. The large circles are positions of the brightest barium jet. F and E indicate locations of Fort Yukon and Ester Dome, respectively.

Fig. 7 Rapid-run magnetic data from College in the interval surrounding the OOSIK barium injection.

Fig. 8 College all-sky camera data. The frames from the release ( $R = 0$ ) through  $15^m20^s$  ( $160^\circ$ ) after the release were 8 sec exposures whereas the remaining frames are 4 sec exposures (on Kodak 2485). The frames are printed with magnetic north up and east to the right. The barium jet is seen near the center of the first two frames. The inserted circles on subsequent frames indicate the 100 km point of the brightest of the observed barium streaks. The auroral arc which intercepts the barium between  $19^m00^s$  and  $18^m40^s$  after the release is part of a spiral, the outline of which is clearly seen in the last frame of the sequence ( $R + 20^m40^s$ ).

Fig. 9 Maps showing relative positions of the aurora and the 100 km altitude projection points of the barium streaks. The initial release projection point is near Venetie (V); E and F show locations of Ester Dome and Fort Yukon, respectively. After the onset

of the substorm, near 16 min after the release, the aurora expands poleward to intercept the generally southeasterly drifting barium. The spiral configuration of the aurora is evident in the last map (Release + 20<sup>m</sup>40<sup>s</sup>).

Fig. 10 Maps showing 100 km-altitude drift velocities of the barium streaks (heavy straight bars) and the auroral lower borders (irregular lines) during the intersection with the poleward expanding aurora. The shear in the drift velocity across the aurora is clearly seen in the panels representing Release + 19<sup>m</sup>07<sup>s</sup> to Release + 19<sup>m</sup>28<sup>s</sup>.

Fig. 11 Drift velocity of the barium and deduced E field near the aurora. Open circles represent end points of velocity (or electric field) vectors. The graph pertains to one of the observed streaks during the period from 18<sup>m</sup>30<sup>s</sup> after the injection to 20<sup>m</sup> after the injection. The points are 6 sec apart in time, and the axes are geomagnetically oriented.

Fig. 12 Comparison between triangulated and theoretical field lines. The triangulation was done using the data from Fort Yukon and Ester Dome and intensified camera data from Johnston Island. The theoretical field line was obtained from the Mead-Fairfield external coefficients (M + F SD) of the super-disturbed magnetosphere ( $K_p > 3$ ) combined with the POGO 10/68 model of the earth's internal magnetic field.

Fig. 13 Part of a Barter Island TV frame (looking south) showing the field lines as delineated by the barium 16 min after the injection. The white dashed line is the theoretical field line which gives the best fit to the bright center arc. The theoretical field

line was derived from the Mead-Fairfield model of the super-disturbed magnetosphere plus the POGO 10/68 model of the internal field. The numbers indicate distance along the field line from the point of injection. The barium-painted field lines are all on the poleward side of the aurora: they appear to be distorted eastward with increasing altitude relative to the theoretical field line.

Fig. 14 Diagram similar to Fig. 13 but after the aurora expanded poleward of the barium ( $E + 19^m33^s$ ). Although the barium streaks are fuzzy in appearance (presumably due to the high drift velocities encountered at this time) the difference in the fit between the observed and theoretical field line shown here and in Fig. 13 is evident. The observed field line is now distorted westward with increasing altitude as compared to the theoretical field line.

Fig. 15 Average magnetic south and west components of the electric field deduced from the drift of the barium streaks. The fields are reduced to the 100 km level. The reversal in the north-south component at the time ( $E + \sim 19$  min) the aurora passes through the L shell occupied by the barium is evident.

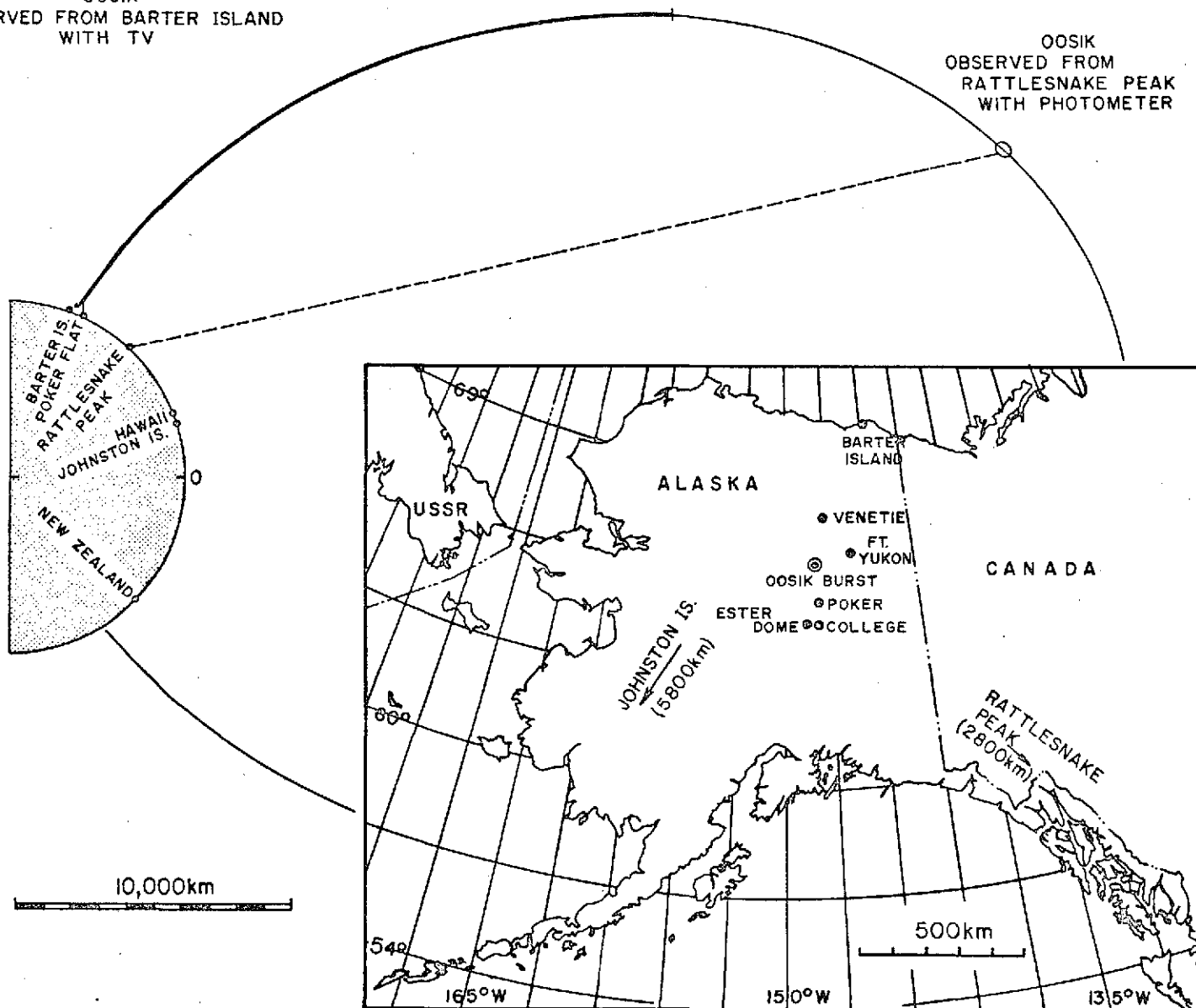
Fig. 16 Magnetic south and west components of the electric field deduced from the drift motion of the 5 brightest rays near the time the aurora expanded poleward through the barium. Each trace represents one of 5 barium jets. The 5 jets were nearly aligned in a magnetic east-west array. High north-south components are seen near the aurora; the reversal coincides with the crossing of the most poleward auroral arc. The field is seen to be directed inward towards the auroral arc.

Fig. 17 Projection into the equatorial plane of the positions of the dominant barium streak and the general location of observed auroras using the POGO 10/68 model plus the Mead-Fairfield super-disturbed external coefficient. Arrows indicate the directions of the equatorial electric field; the field magnitude in mV/m is shown beside the three vectors; other numerals indicate time in minutes after the injection event.

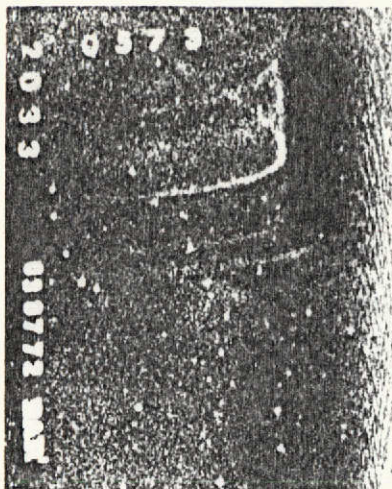
Fig. 18 Horizontal disturbance vectors at various northern hemisphere stations at 0720 UT (21 minutes after release). Note the lack of activity in the midnight sector. The OOSIK Substorm is localized in the evening sector and is apparently unrelated to the large negative bay observed at Narssaurssauq in the late morning sector.

OOSIK  
OBSERVED FROM BARTER ISLAND  
WITH TV

OOSIK  
OBSERVED FROM  
RATTLESNAKE PEAK  
WITH PHOTOMETER







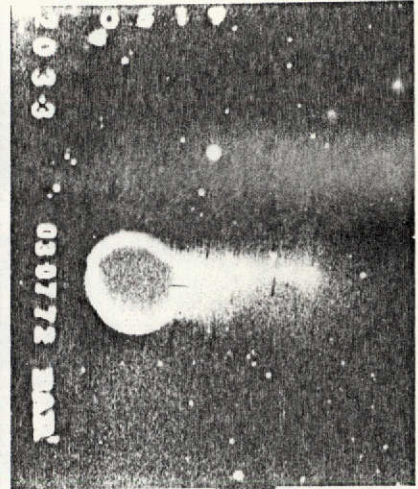
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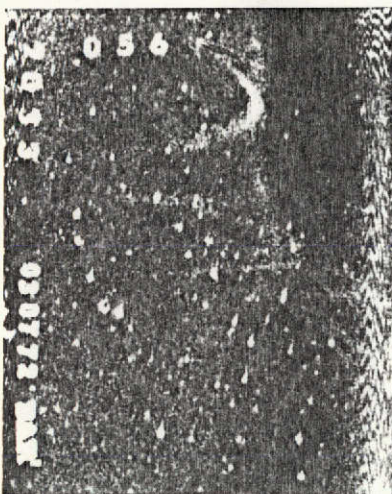
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E+5



06 59 17

E+:17<sup>s</sup>



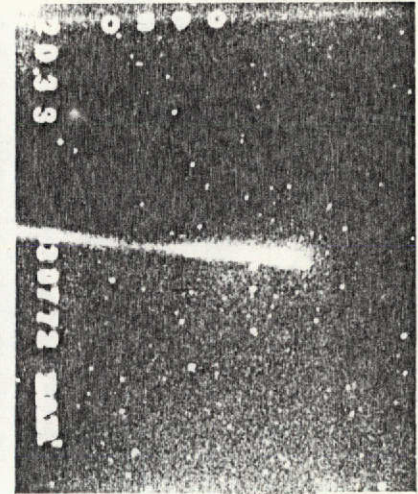
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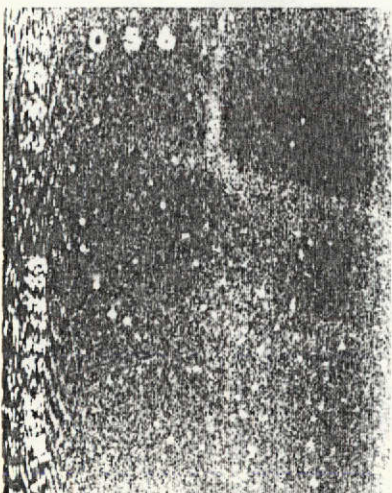
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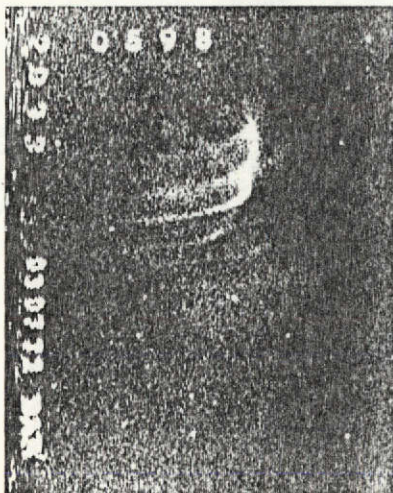
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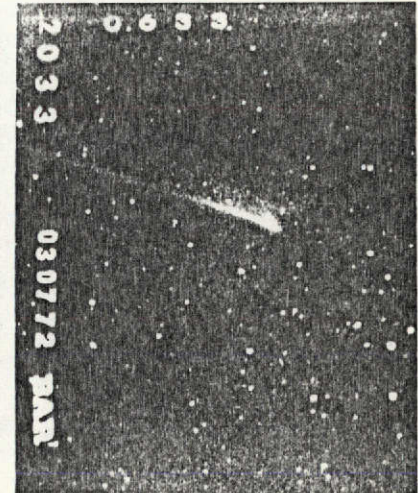
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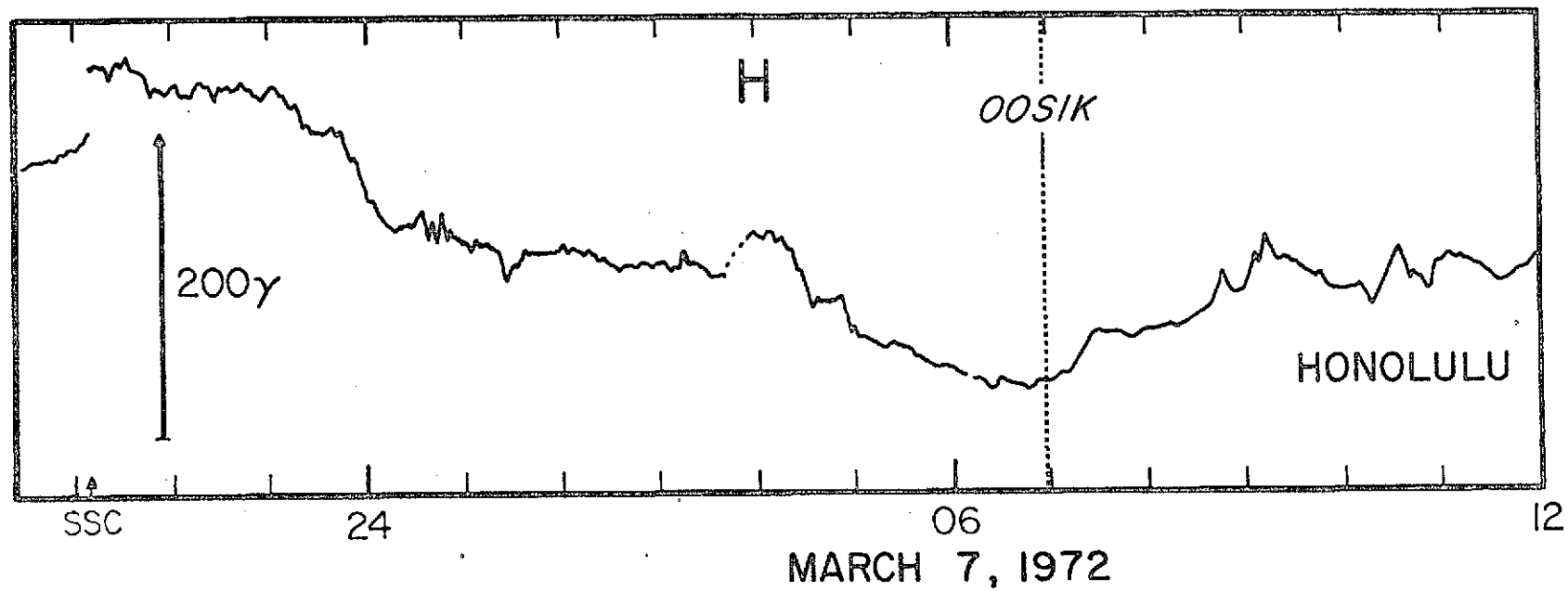
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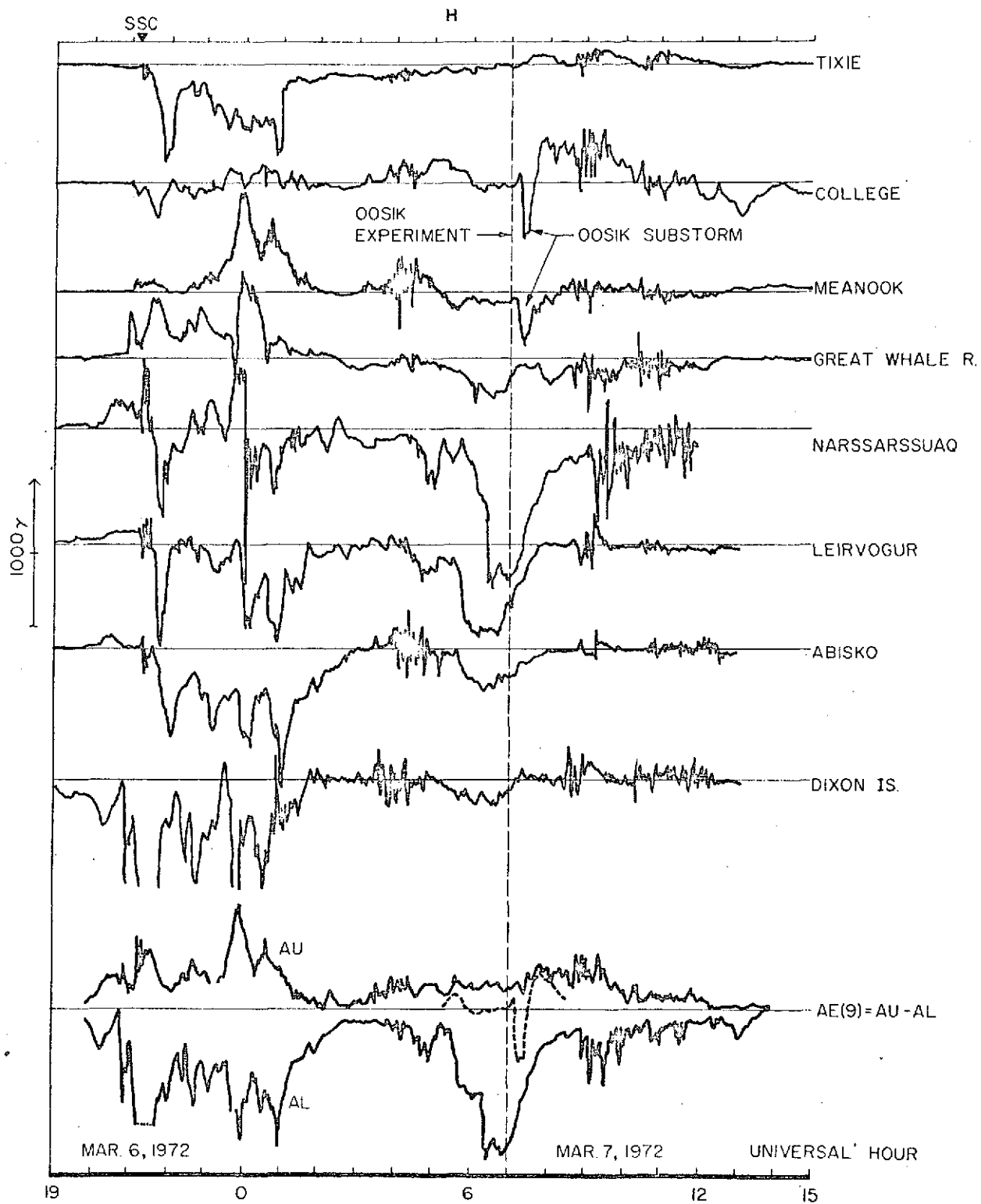


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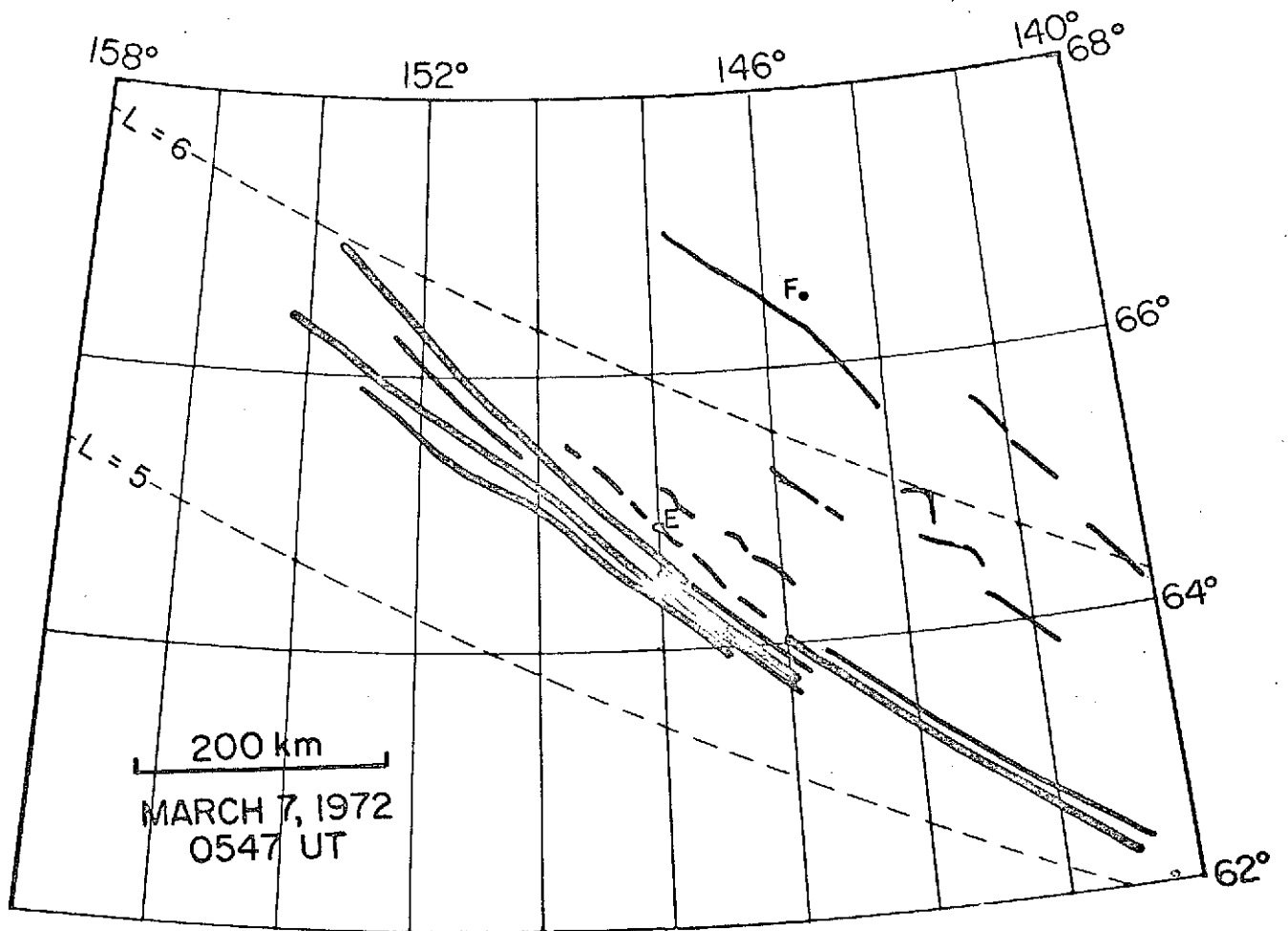
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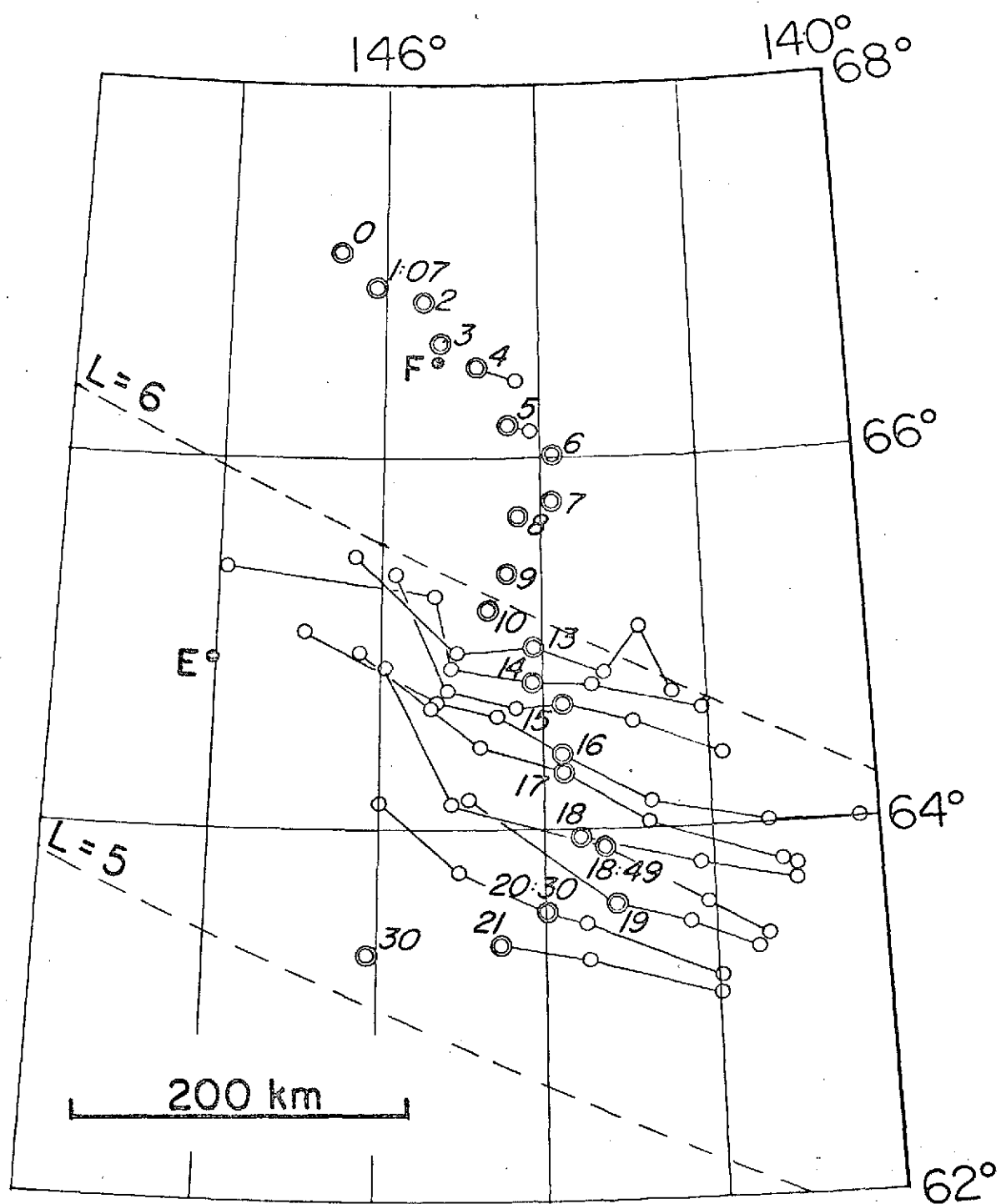


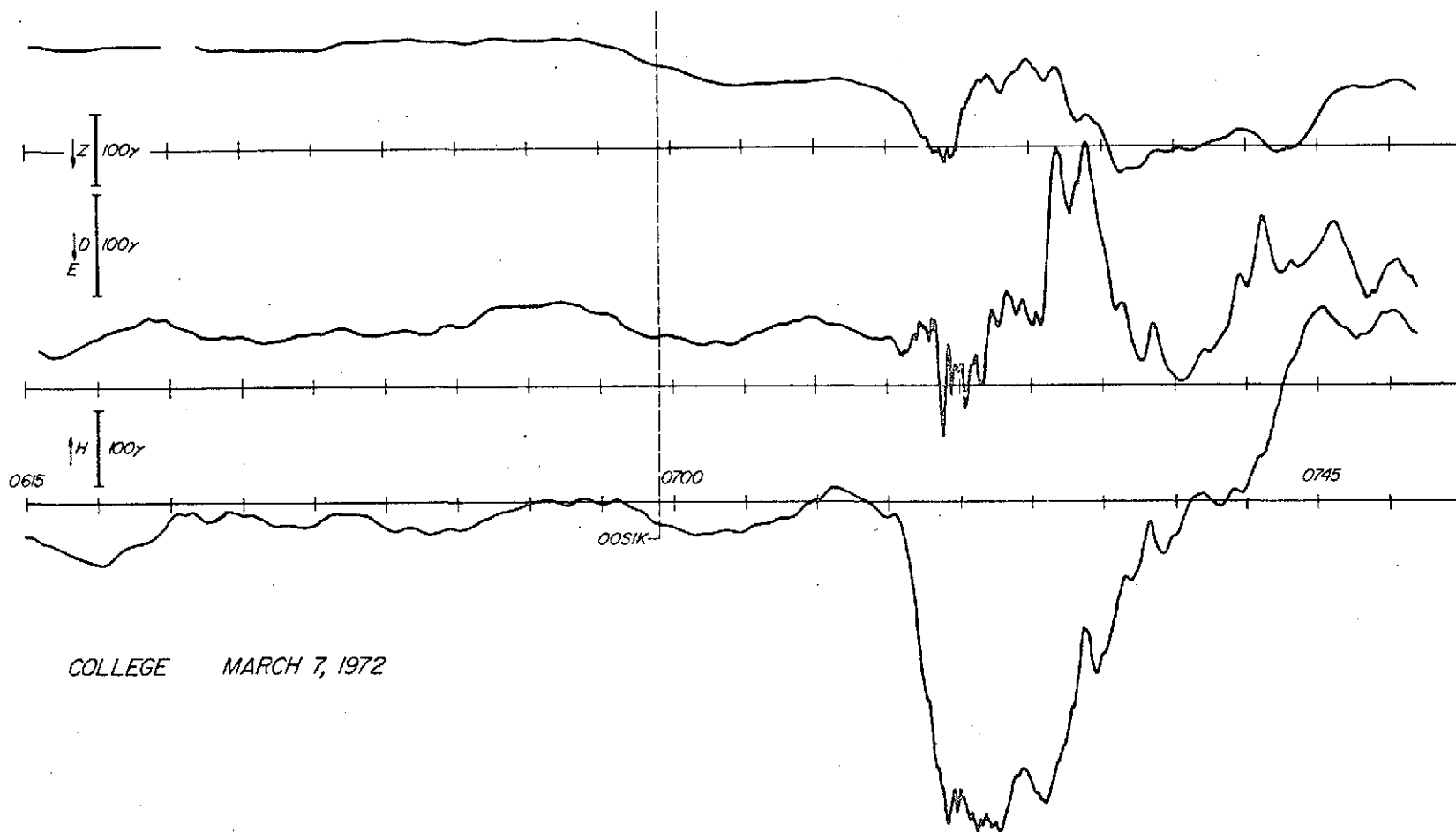








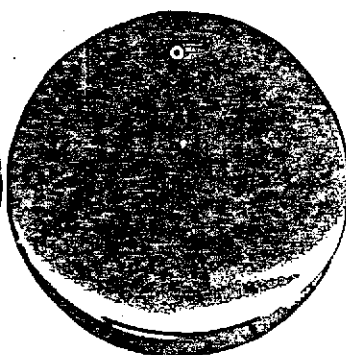




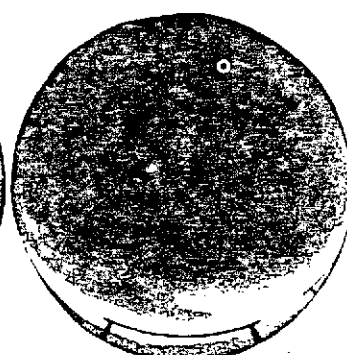
COLLEGE MARCH 7, 1972



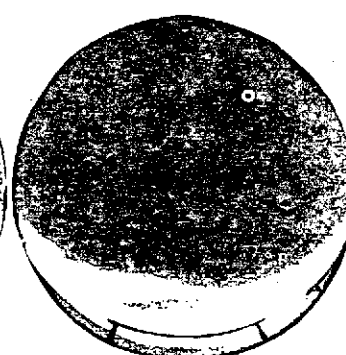
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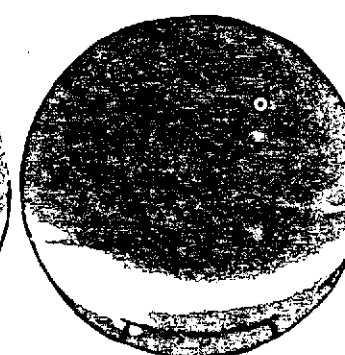
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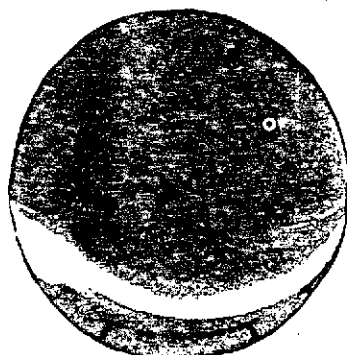
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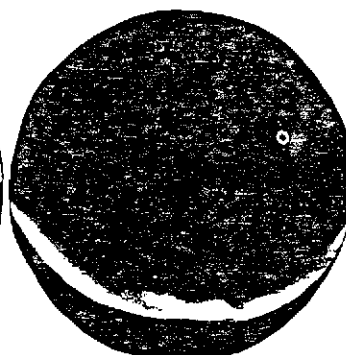
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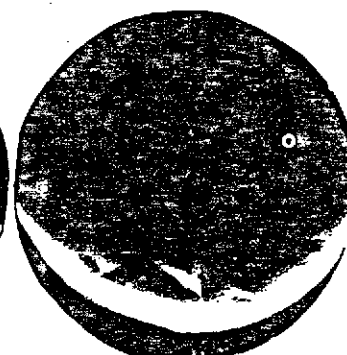
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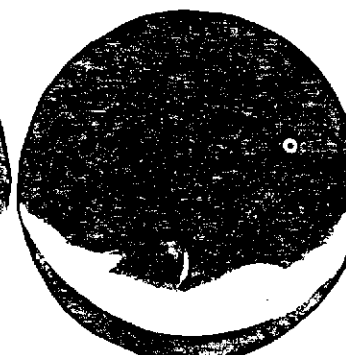
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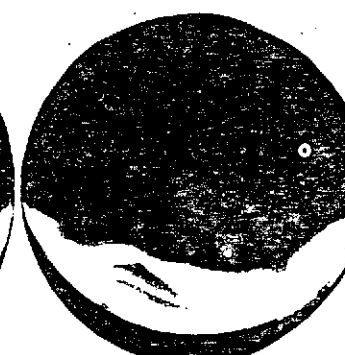
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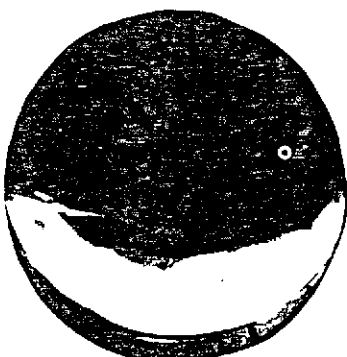
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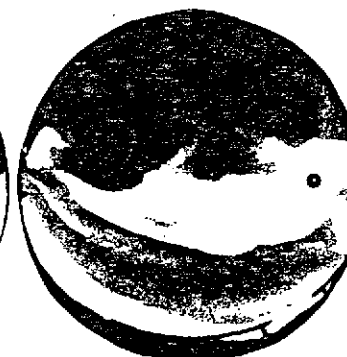
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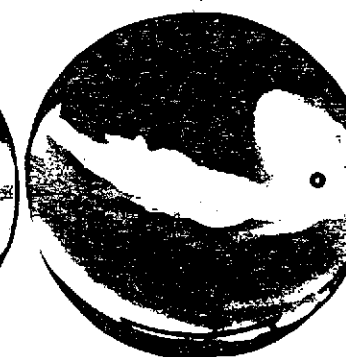
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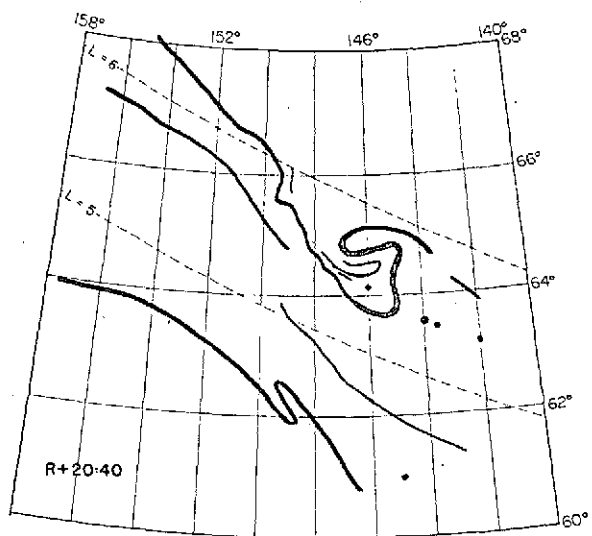
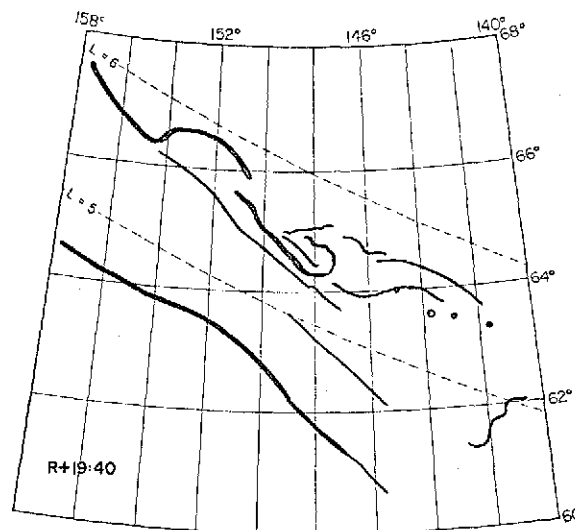
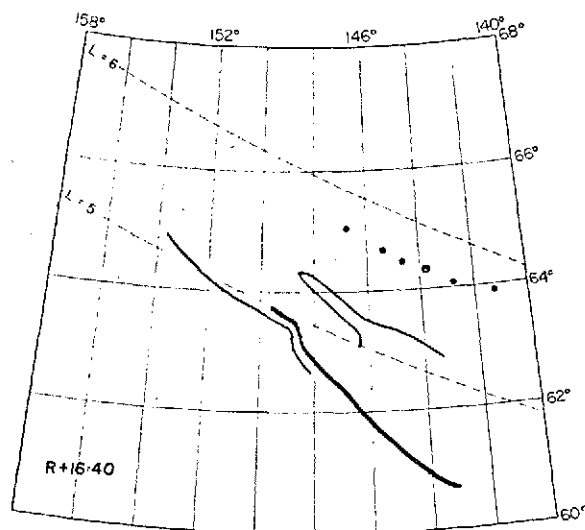
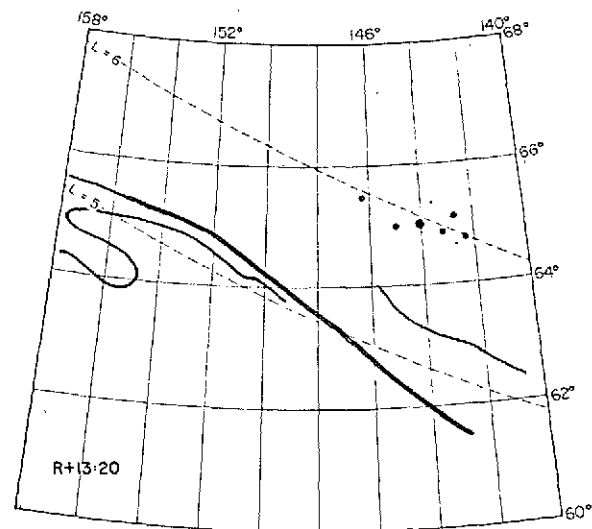
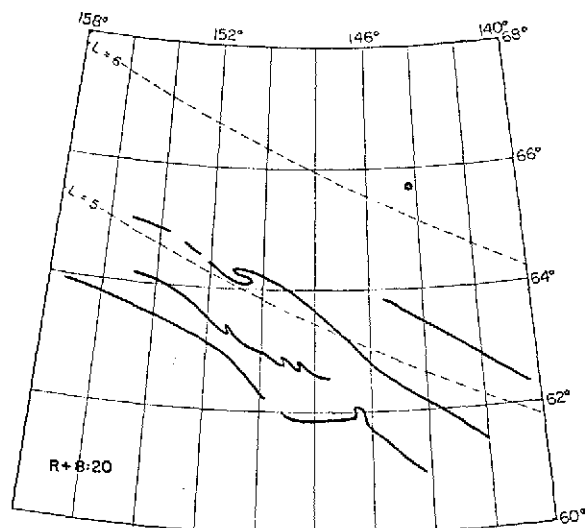
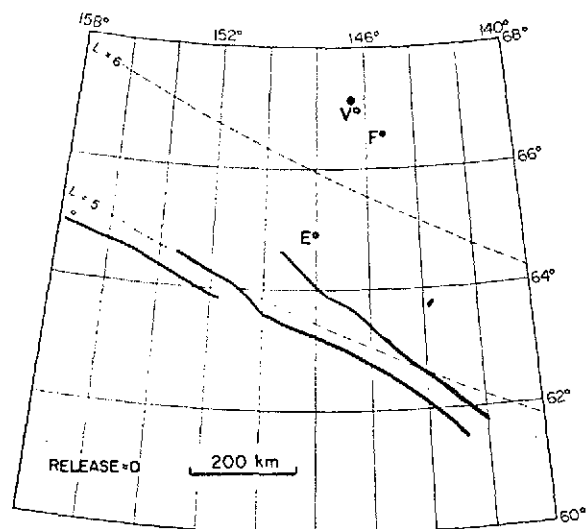
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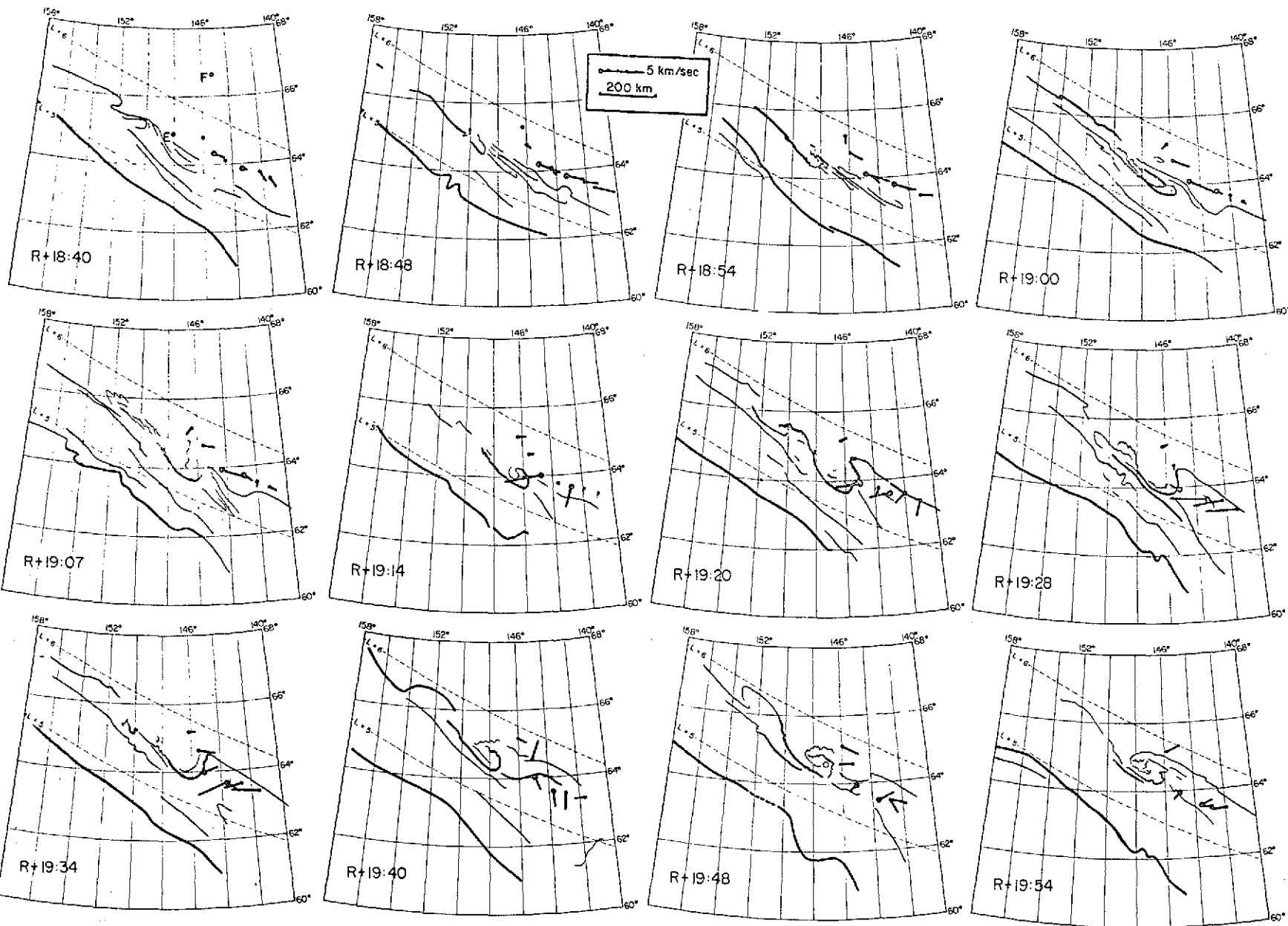


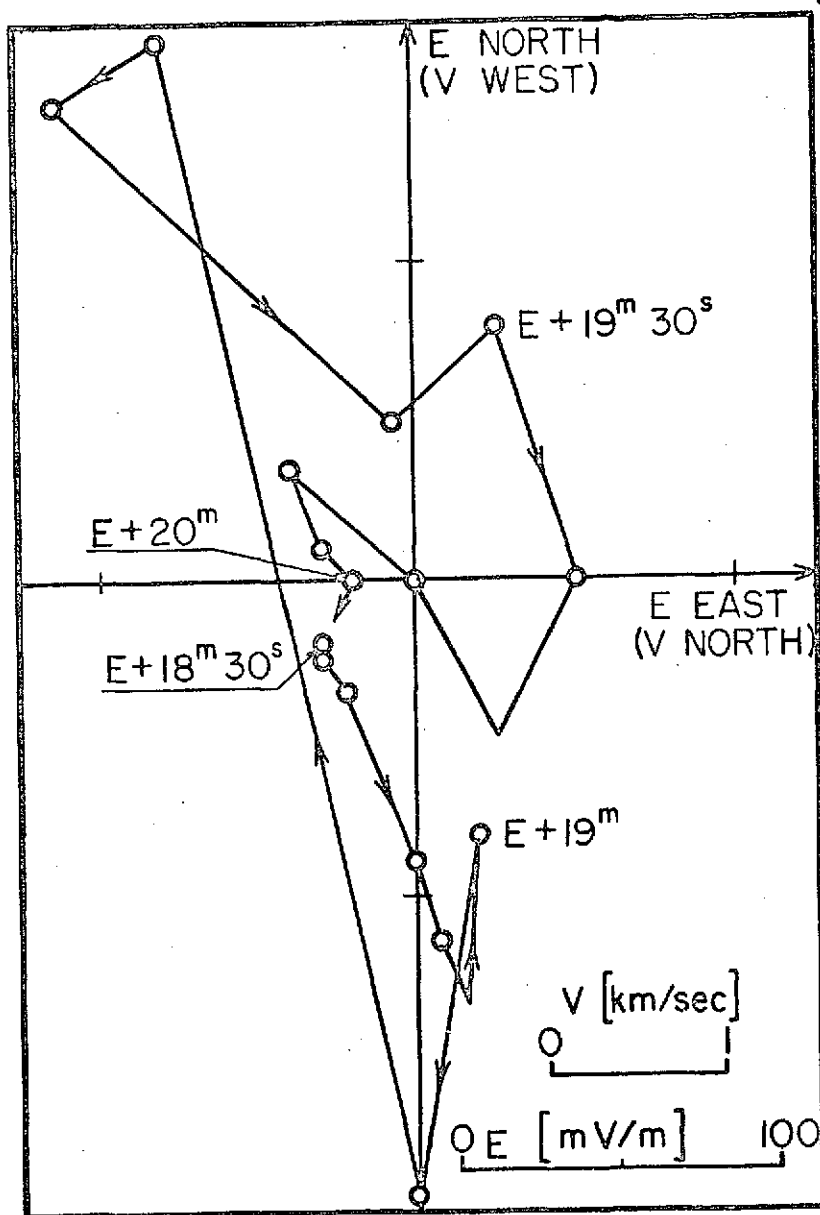
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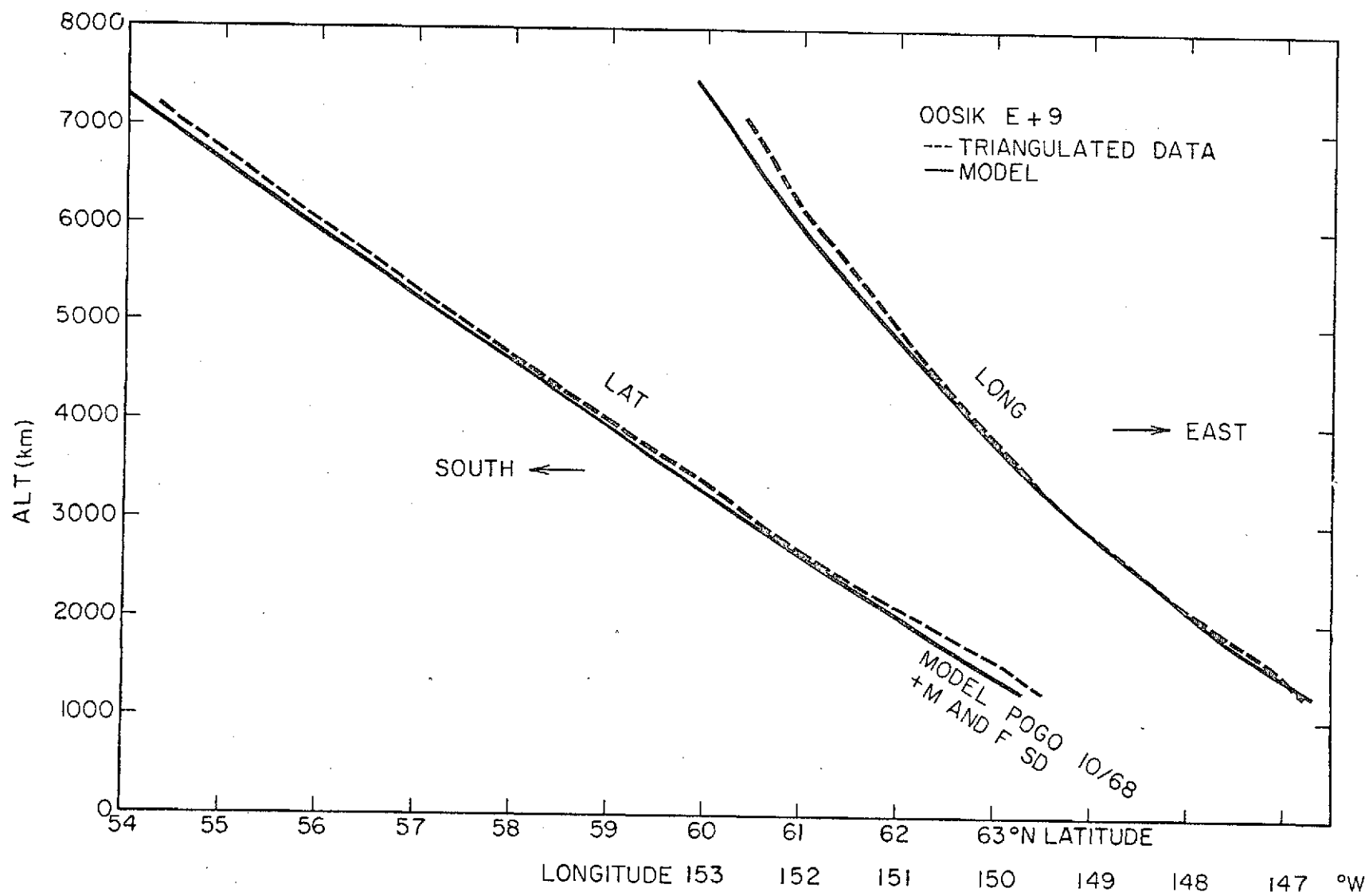


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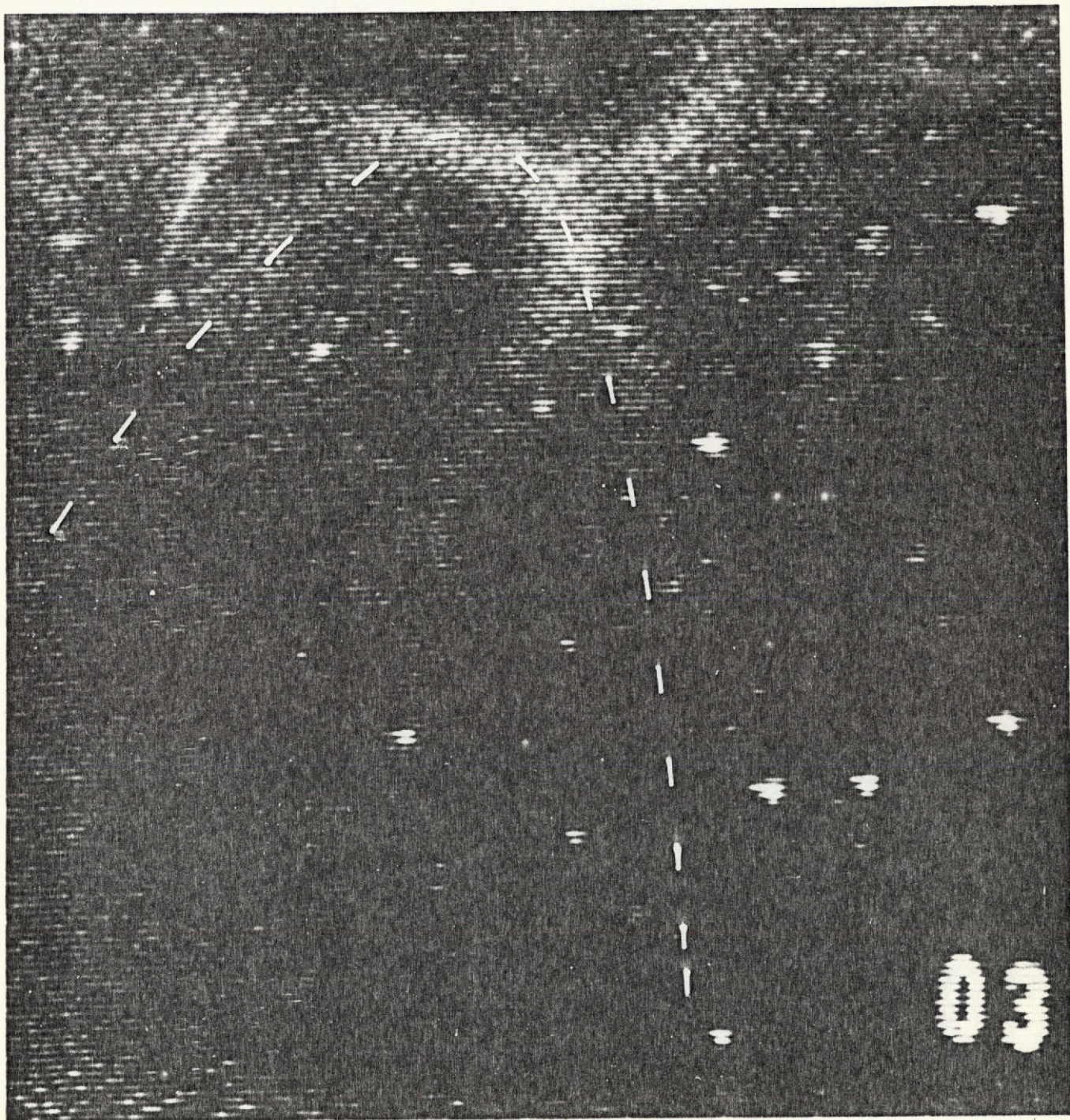


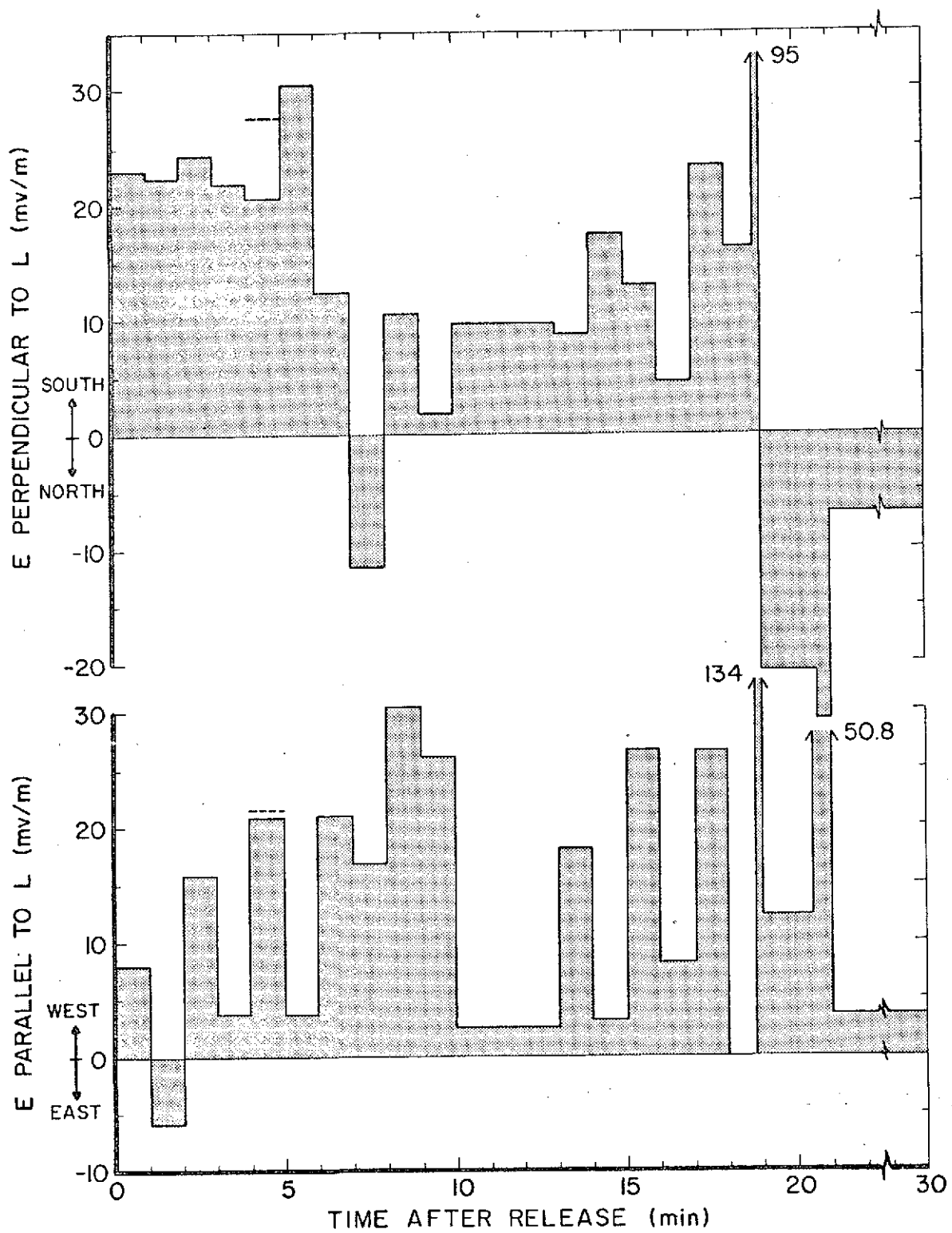


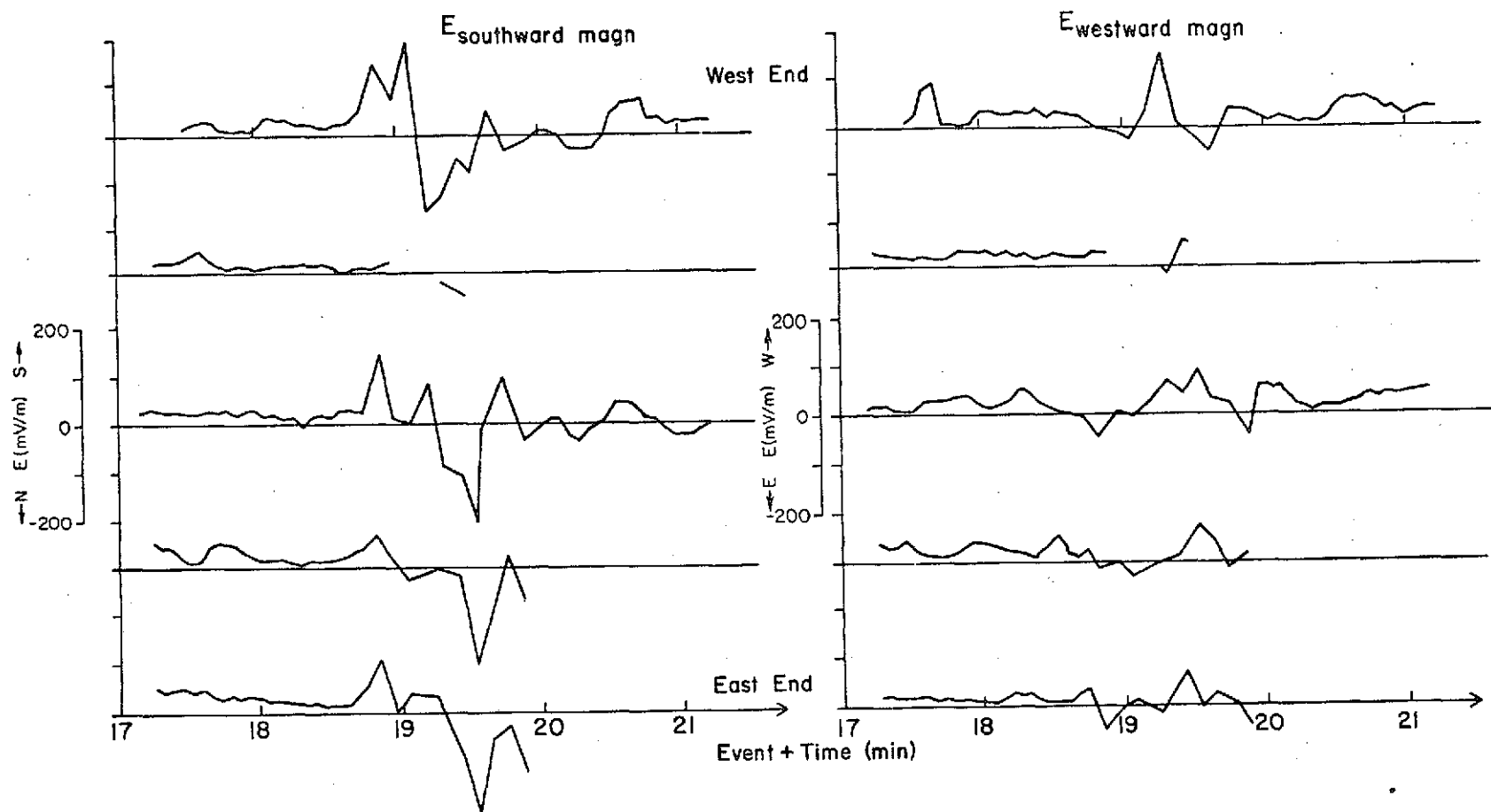


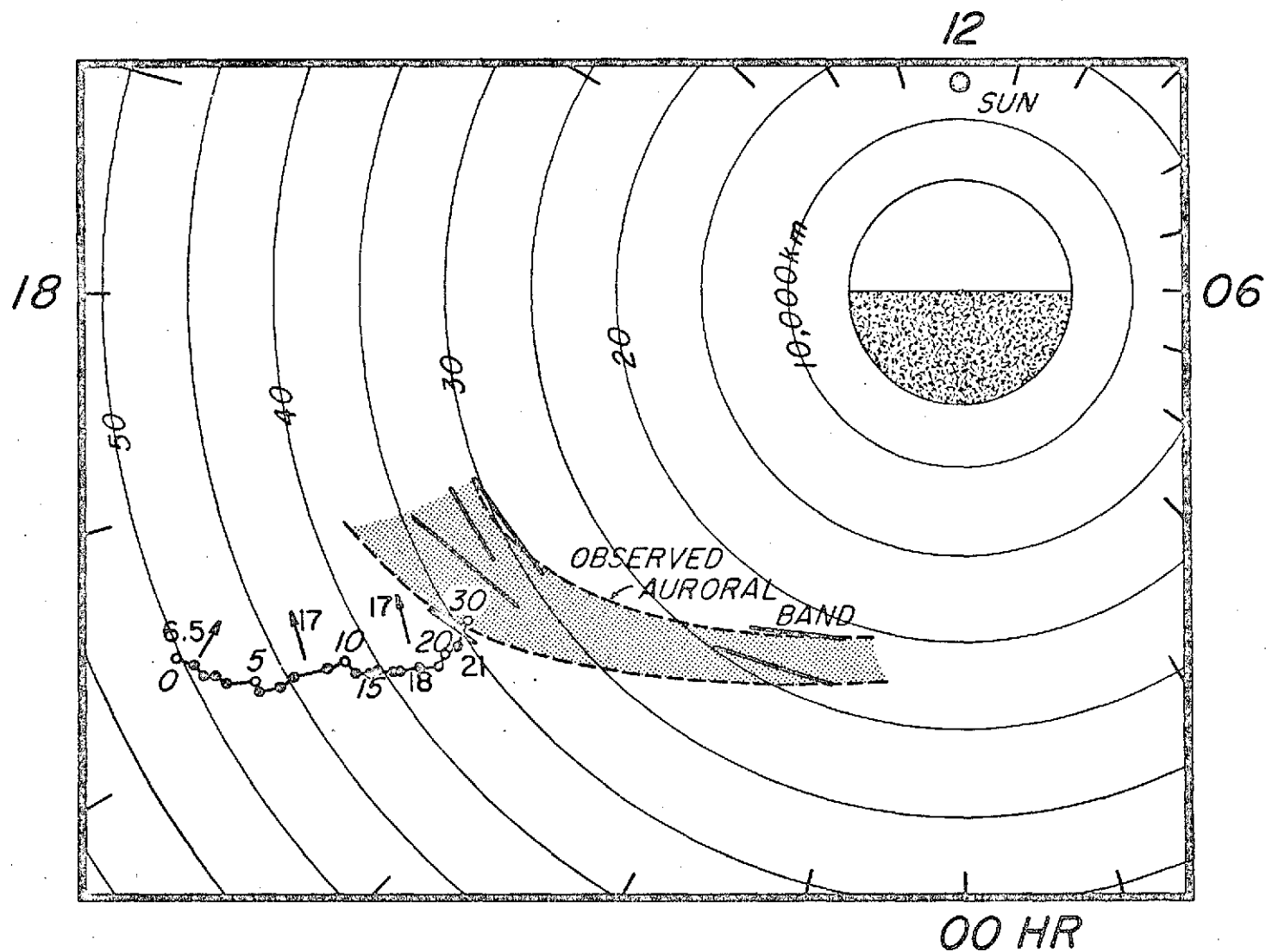






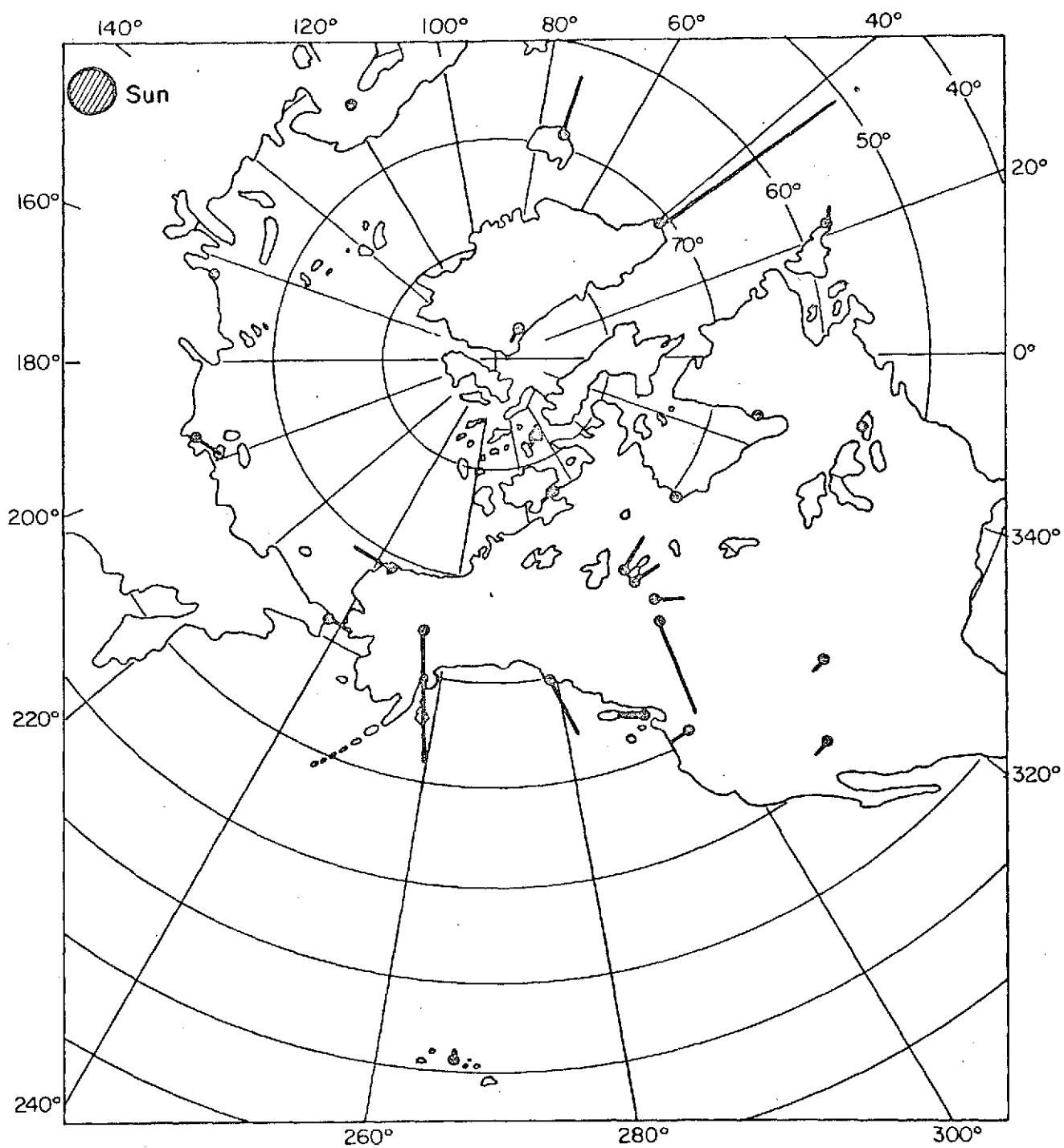






*appears to be error of  
19 min*





0720 UT  
7 MAR 1972

OBSERVATION OF AURORAL BIRKELAND CURRENT SHEET FROM  
DISTORTION OF A BARIUM PLASMA JET

by

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ABSTRACT

During the OOSIK barium shaped-charge plasma injection experiment over Alaska conducted at 0659 U.T. on March 7, 1972,  $L = 6.6$  magnetic field lines were made visible and observed over a length of 13,000 km. When compared against the star background and the best fitting Mead-Fairfield super-disturbed field model, the traced field lines were bent in one sense when the aurora was south of the field lines and in the opposite sense after the aurora moved north of the traced field line. The resulting shear in the magnetic field across the auroral form (a portion of a spiral) is equal to that produced by an upward current sheet of 0.08 amp/m. Rapid drifts of the barium flux tubes near the auroral encounter were equivalent to  $\underline{E} \times \underline{B}$  drift of  $|\underline{E}| > 200$  mV/m at the 100 km level. The electric field was directed inward to the auroral form, consistent with an excess negative space charge.

The OOSIK barium plasma injection experiment (carried out over Alaska on March 7, 1972 at 0659,  $L = 6.6$ ) employed the detonation at 540 km altitude of a high explosive shaped-charge with a hollow conical liner of barium metal to create a field-aligned jet of plasma travelling upwards with a velocity distribution from 8-15 km/sec. The visible flux tube (or flux tubes after the original split into several) were observed with TV systems from a station, Barter Island, 500 km north of the injection point. This station allowed optimum view angles for comparison with theoretical field models, as some 13,000 km of field line could be seen in one TV picture. The barium flux tubes were all north of the existing auroral forms for 19 minutes although they drifted southwards through this time. At first the aurora remained relatively quiescent and stationary but, at 17 min after the barium injection, the aurora formed a classic spiral formation and expanded polewards of the barium. Comparisons of various available field models including the external, time- and magnetic activity-dependent coefficients of Mead and Fairfield (1973) all showed a systematic divergence of the barium flux tubes increasing with altitude. The best fit was produced by use of the POGO 10/68 model (Cain and Langel, 1971) plus the Mead-Fairfield super-disturbed coefficients. Prior to 19<sup>m</sup>40<sup>s</sup> following barium injection, the distortion of the barium marked field line was towards the east. After barium injection plus 19<sup>m</sup>40<sup>s</sup> (the auroral encounter), the distortion was towards the west. Figure 1 illustrates the situation and an upward current sheet near the polewards edge of the spiral of 0.08 amp/meter which would produce the observed shear in the magnetic field. Hallinan et al. (1972) and Webster and Hallinan (1973) have proposed that the auroral spiral configuration is the result of instability in a field-aligned sheet current when the



current reaches a threshold value compatible with our calculated current.

Also observed at the time of the auroral encounter with the barium flux tubes were very rapid motions consistent with a large electric field ( $E > 200$  mV/m) directed inward towards the auroral form at the northern edge of the spiral. If the electric field were due to excess negative charge enough to carry the required current, it implies the presence of positive ions as well. A full description of all results of the OOSIK experiment is in preparation.

#### ACKNOWLEDGEMENTS

We thank the many persons who contributed to the planning, execution and analysis of the OOSIK experiment. Work done by Los Alamos Scientific Laboratory was under the auspices of the U. S. Atomic Energy Commission. Work performed by the Geophysical Institute, University of Alaska was sponsored by NASA Grants NGR-02-001-087 and NGR-02-001-088 and partially by NSF Grant GA-19625.

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#### FIGURE CAPTION

Schematic diagram illustrating the increasing displacements with altitude of the primary OOSIK barium plasma flux tube from the best fit model field line. The distortion was eastward when the flux tube was north of the aurora, but switched to westward when the expansion of a classic spiral resulted in the flux tube being located south of an arc on the northern boundary of the spiral. The observed distortion and shear in the magnetic field line configuration extended beyond 10,000 km altitude, and is consistent with an upward sheet current at the southern edge of the spiral of 0.08 amps/m.

